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SUSTAINABILITY ASSESSMENT OF THE HOT WATER EXTRACTION BIOREFINERY PROCESS USING A PHASED IMPLEMENTATION APPROACH

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Ce mémoire intitulé:

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DEDICATION

To my Mother
For her support, encouragement, and constant love throughout my life.

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RÉSUMÉ

L'industrie canadienne des pâtes et papiers (P&P) est confrontée à une concurrence mondiale sans précédent. Ceci l'oblige à développer des solutions innovantes pour maintenir sa compétitivité. dans un contexte où les préoccupations environnementales sont grandissantes, en particulier celle du réchauffement climatique et celle de la consommation des ressources fossiles, qui ont mené à l'établissement de réglementations environnementales plus strictes. Le concept de bioraffinage est de plus en plus considéré comme une solution prometteuse pour améliorer la rentabilité et la performance environnementale des usines de P&P ainsi que pour soutenir la transformation du modèle d'affaire des compagnies forestières.

La rétro-installation d'un procédé de bioraffinage dans une usine existante présente de nombreux défis dus à l'incertitude dans la conception de procédé, la mise à l'échelle de technologies émergentes, le choix des matières premières, le choix de la technologie de conversion, la performance des bioproduits en adéquation avec les besoins du marché ciblé, les problèmes potentiels d'intégration avec les procédés existants, le manque de capitaux et le financement. Ces incertitudes engendrent de nombreux risques commerciaux et technologiques. Des stratégies d'implantation incrémentale basées sur une approche systématique par phase peuvent être suivies pour atténuer les risques associés aux projets de transformation en bioraffinerie. Les projets de bioraffinerie ont l'objectif de développer des produits et de l'énergie provenant de sources renouvelables. L'identification de la stratégie la plus durable est donc critique pour la mise en œuvre réussie des projets de bioraffinerie. L'évaluation de la durabilité d'une stratégie de bioraffinage peut être faite en considérant les facteurs les plus importants identifiés par une analyse systématique. Une stratégie de bioraffinage peut être considérée comme durable lorsqu'elle apporte de la rentabilité, de la performance environnementale, de la compétitivité à long terme et qu'elle présente des mesures d'atténuation des risques technologiques et de marché.

L'objectif de cette thèse est de mettre en oeuvre une méthodologie pratique et systématique pour l'évaluation des stratégies d'implantation du bioraffinage basé sur

l'extraction à l'eau chaude (HWE) des hémicelluloses, considérant la durabilité et le potentiel de réduction des risques commerciaux et technologiques. La méthodologie est validée en utilisant une étude de cas impliquant l'intégration à une usine existante d'un procédé de bioraffinage basé sur HWE. Les procédés considérés incluent l'extraction des hémicelluloses et son traitement ultérieur selon différentes applications: production de biogaz, production d'hémicelluloses pour l'alimentation animale, production d'hémicelluloses pour la fabrication d'un sucre à cinq carbones (sucre C5), production d'un sucre C5 et production de furfural. Le sel d'acétate est coproduit dans toutes les options de traitement à l'exclusion du celle pour le biogaz. Suite à l'identification des couples procédé/produit prometteurs, des scénarios d'implantation par phase sont définis pour atténuer les risques financiers, commerciaux et technologiques. Ensuite, les outils d'ingénierie des systèmes sont utilisés pour évaluer la performance en durabilité des options de procédé et de leurs scénarios d'implantation par phase à court et à long terme. Finalement, les résultats économiques, environnementaux et d'analyse des risques sont analysés ensembles afin d'identifier la stratégie de bioraffinage HWE la plus durable.

Les résultats de l'analyse économique ont prouvé que sans subvention du gouvernement aucune des options de bioraffinage HWE ne semble économiquement prometteuse, sauf celle produisant le sucre C5 qui obtient un taux de retour interne (TRI) de 25%. Néanmoins, considérant l'évaluation préliminaire des risques, les risques associés à cette option ont été identifiés comme étant relativement élevés. En incluant les subventions, les résultats économiques sont radicalement changés et toutes les options de bioraffinage définies ont montré une rentabilité attrayante - à l'exclusion du biogaz. Il a été montré que le TRI est particulièrement sensible à l'inclusion des subventions, en particulier dans le cas des stratégies à faible coût en capital. Considérant les résultats de l'analyse des scénarios d'implantation, il a été prouvé que la stratégie implantée en deux phases (Phase I : sirop d'hémicelluloses pour fabrication de sucre C5 et sel d'acétate, Phase II : sucres C5 et sel d'acétate) présente une meilleure atténuation des risques que les stratégies implantées en une seule phase directement. En ce qui concerne l'analyse des impacts environnementaux (analyse de cycle de vie conséquencielle "du berceau à la porte"), l'écorce, les produits chimiques et le transport des produits ont été identifiés comme étant

les principales sources d'impacts. Les options de bioraffinage, y compris le sirop d'hémicelluloses pour les sucres C5 et les sucres C5 présentent respectivement des réductions des gaz à effet de serre (GES) de 80 % et 68 %. En outre, les résultats montrent une amélioration considérable de la performance (plus de trois fois) dans la catégorie d'impact sur la santé humaine.

En raison de la cohérence entre les résultats économiques, environnementaux et d'analyse des risques, l'identification de la stratégie la plus durable est simple. La coproduction du sel d'acétate et d'hémicellulose pour la fabrication de sucre C5 en phase I suivi par la coproduction du sel d'acétate et du sucre C5 en phase II, apparaît comme étant la stratégie de bioraffinage la plus prometteuse et durable.

ABSTRACT

Canadian pulp and paper (P&P) industry has encountered the challenge of an ever-growing level of global competition in the product market. This in turn implies the necessity for innovative solutions for the P&P industry to maintain its competitive position. In addition, P&P companies have faced further restrictions due to the existence of strict environmental regulations; increase of environmental concerns regarding the global warming and limitations in the fossil-based resources. Biorefining is increasingly considered as an alternative solution for enhancing P&P mill's profitability, improving their environmental performance and facilitating their market transformation.

Retrofitting a biorefinery process into an existing mill introduces numerous challenges due to uncertainties in process design and scale-up, various types of feedstock, different biorefinery conversion technologies, bioproduct properties and market position, potential problems in the mill's process due to biorefinery integration and lack of capital and financing. These uncertainties result in several market and technology risks. Strategies such as incremental implementation of the biorefinery processes based on a systematic phased approach can be followed for mitigating the risks associated with biorefinery projects. In addition, the main objective of implementing a biorefinery project is to develop sustainable sources of renewable energy and products. Therefore, identification of the most sustainable strategy plays a significant role in the successful implementation of biorefinery projects. Several indicators can be defined for the sustainability evaluation of biorefinery processes, but a systematic analysis can help identifying the most important factors to consider. A sustainable biorefinery implementation strategy is the one that provides profitability and long-term competitiveness, mitigates market and technology risks in a proper manner and presents remarkable environmental performance.

The objective of this thesis is to apply a systematic and practical methodology for evaluating the hot water extraction-based (HWE) biorefinery implementation strategy, using a perspective of sustainability and assessing the potential for technology and market risk mitigation. The methodology is demonstrated by using a case study that involves the integration of HWE pretreatment process into an existing P&P mill. The biorefinery process includes hemicellulose extraction and its further processing for

different applications including biogas, hemicellulose for animal feed, hemicellulose for C5-sugars, C5-sugars and furfural. Acetate salt is the by-product of all the process options excluding the biogas. Following the identification of feasible HWE-based process-product alternatives, phased approach scenarios are developed to mitigate the financial, market and technology risks. Then, systems engineering tools are employed to assess the economic, environmental and risk performance of the developed process options in short-term and long-term and to evaluate metrics for the sustainability evaluation. Finally the results of the analysis are interpreted and analyzed to identify the most sustainable HWE-based biorefinery process option.

Results of the economic analysis proved that before the inclusion of government subsidy and except for C5-sugars option with the Internal Rate of Return (IRR) of 25%, none of the HWE-based biorefinery options looked economically promising. Nonetheless, according to a preliminary risk assessment, market and technology risks associated with C5-sugars option were identified to be relatively high. By including subsidy, the economic landscape changed drastically and all the defined biorefinery options, excluding biogas, showed considerable project profitability. It was realized that IRR was particularly sensitive to subsidy, specifically in the case of low capital cost process options. Considering the results of risk analysis, it was proved that the two-phase strategy, which aggregated the production of acetate salt and hemicellulose for C5-sugars in phase I and C5-sugars and acetate salt in phase II, had better risk mitigation performance, when compared with single-phase strategies. Regarding the environmental analysis (“Cradle-to-gate” consequential LCA), bark, chemicals and product transportation identified to be as main sources of impacts. Biorefinery options including hemicellulose for C5-sugars and C5-sugars presented GHG reduction of 80% and 68%, respectively. Also, these options proved a considerable improvement of more than three times in the human health impact category, relative to the existing processes at the mill.

Due to the consistency between the economic, environmental and risk analysis results, identification of the sustainable process option is straight-forward. The two-phase option including acetate salt and hemicellulose for C5-sugars application in phase I and acetate salt and C5-sugar in phase II was identified to be the most promising and sustainable biorefinery process option.

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LIST OF ABBREVIATIONS

NREL	National Renewable Energy Laboratory
IEA	International Energy Agency
P&P	Pulp and Paper
GHG	Greenhouse gas
VPP	Value Prior to Pulping
HWE	Hot water extraction
API	American Process Inc.
MCDM	Multi-Criteria Decision Making
SWOT	Strength, Weakness, Opportunities and Threats
PEST	Political, Economic, Social, and Technological
ROI	Return on investment
NPV	Net present value
IRR	Internal Rate of Return
OPEX	Operating Cost
CAPEX	Capital cost
BAT	Best Available Technology
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact assessment
LUC	Land Use Change
ILUC	Indirect Landuse Change
NEV	Net energy value
CCF	Cumulative Net Cash Flow
A.A.	Acetic Acid
A.S.	Acetate salt
M	Million or 1Å~10^{6}
Hemis	Hemicellulose
F.O.B.	Freight On Board
EPC	Engineering, procurement and construction

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INTRODUCTION

Problem statement

In recent years, North American forestry companies and particularly Pulp and Paper (P&P) industry, have suffered from serious financial problems. Although P&P is one of the most dominant industries in Canada, it faced a significant decline in the product demand over the past years due to the strong competition in the global market, especially with countries located in Asia, also high production costs related to energy and biomass. To overcome this crisis while remaining competitive in the market, various effective short-term and long-term strategies have to be adopted. One alternative solution for the forestry companies is to consider the implementation of biorefinery technologies that have been emerging in recent years, in order to improve their economic and environmental performance. Biorefinery integration into the existing P&P mill provides promising opportunities due to the existence of the required utility systems, existing feedstock supply chain networks and product delivery systems as well as the potential for mass and energy integration between the existing mill and new biorefinery processes. By applying the biorefinery integration, companies will not only be able to continue the production of their traditional forestry products, but also will diversify their product portfolio by having added-value products.

Bioenergy and bioproducts have a remarkable influence on the transition of society towards a sustainable, bio-based economy. Although biorefinery implementation illustrates considerable economic opportunities and environmental improvement, there are various challenges in the design and implementation of biorefinery projects that are needed to consider:

- In the biorefinery process, there is a wide range of biomass feedstock, biorefinery conversion technologies and pretreatment methods that lead to different production pathways and product portfolios.
- Biorefinery projects are capital intensive and in many cases, the cost of bio-based production exceeds the cost of petrochemical production.
- There are market and technological risks associated with these projects. Technology maturity and scale-up complexity of biorefinery technologies, process flexibility and operational robustness, chemical properties of bioproducts substituting or replacing

agricultural or petrochemical equivalents, available downstream market for the new bioproducts, possible impacts on the core process of the existing mill due to the biorefinery integration are instances of these risks.

The main objective of implementing a biorefinery project is to develop sustainable sources of renewable energy and products. Traditionally, sustainability evaluation is performed by taking into consideration the economic, environmental and social performances. Due to ongoing challenge for the sustainable development of forest biorefineries, there is a need to define a practical and systematic assessment methodology, which not only considers economic profitability and environmental improvements but also, takes into account market and technology risk mitigation approaches.

As a solution with respect to the limited capital resources, also the existing technological and market risks, forestry companies are recommended to consider incremental project implementation and using a phased approach. Phased implementation assists P&P industries to incrementally transform their business model to achieve short- and long-term strategic objectives.

Development of biorefinery projects should be planned and designed. Detailed analysis of the potential configurations at the early design stages is necessary for integrating biorefineries into existing P&P mills. Sustainable design of a biorefinery can take place by performing various systematic case studies and by developing analytical methods to compare the economic, environmental and risk analysis impacts of different separation and conversion processes to frame the choice of the best biorefinery option. With well-planned and careful development of bioproduction pathways, biorefinery processes can be regarded as the foundations of a sustainable future.

Objectives

As explained previously, the major objective of this thesis is to present a systematic and practical methodology for evaluating the sustainability of HWE-based biorefinery. Before starting the evaluation steps, the scope of the sustainability assessment has to be defined and the evaluation metrics suitable for the case study context should be identified. The sustainability evaluation of the biorefinery processes can be performed using the systems engineering tools to assess the market and technology risks and techno-economic and environmental parameters.

Based on this objective, the main hypothesis of this work entitled "Sustainability assessment of the HWE-based biorefinery process using a phased implementation approach" was formulated:

> *Development of hot water extraction biorefinery process is preferred using a phased-implementation approach, and the sustainability of this can be assessed through the combination of risks analysis and techno-economics and life cycle assessment.*

This can be divided into two sub-hypotheses:

- *By assessing the phased implementation approach, it can be shown that this approach provides the most sustainable and risk mitigated implementation alternative for the HWE-based biorefinery process.*
- *By considering metrics calculated using techno-economics and LCA, and coupling these with risk considerations, a clarified perspective can be obtained regarding the sustainability of biorefinery implementation strategies, and an investment decision.*

The problem statement and the hypothesis call for the development of a systematic methodology that exploits the sustainability evaluation of the HWE-based biorefinery process in a systematic and practical approach. As such, the formulation of the methodology was guided by the following main objective:

> *To apply a systematic and practical methodology for evaluating the HWE-based biorefinery implementation strategy, using a perspective of sustainability and assessing the potential for technology and market risk mitigation.*

The accomplishment of the main objective was tied to following specific-objectives:

- *To define candidate approaches for HWE-based biorefinery processes to potentially mitigate market and technology risks associated with the biorefinery process, considering phased implementation.*
- *To evaluate the environmental impacts, techno-economic potentials and market and technology risks associated with HWE-based candidate biorefinery processes, in order to assess the sustainability of the different implementation pathways.*

Thesis organization

This thesis is organized as follows: In chapter 1, the relevant literature is reviewed in order to identify the gaps in the body of knowledge. Chapter 2 presents the methodology developed in this thesis, and the case study to which the methodology is applied. Chapter 3 synthesizes the results obtained in the process of demonstrating the methodology. In chapter 4, overall conclusions are given, followed by chapter 5, which presents the recommendations for future work. In Appendices A to B the articles that are going to be submitted to peer-reviewed scientific journals are given. The link between the hypotheses and publications are illustrated in Figure 0-1.

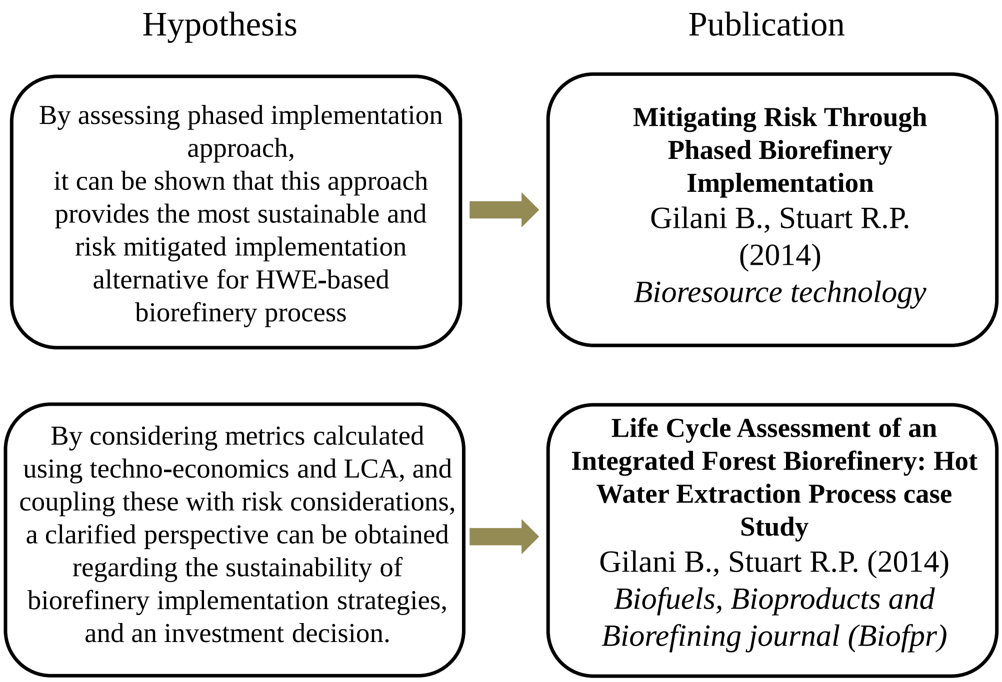

Figure 0-1 Linkage between hypothesis and publications

CHAPTER 1 LITERATURE REVIEW

1.1 Biorefinery processes

Global energy requirement is fulfilled by fossil fuels that are of limited resources, with critical environmental problems for instance increase in greenhouse gas emissions. Due to current interest in moving towards sustainability, industrial facilities are willing to utilize renewable resources like biomass that can contribute to lowering the dependency on fossil-based resources. A similar system to a petroleum refinery is called biorefinery and is related to the production of multiple chemicals and fuels from biomass (Fernando et al., 2006). National Renewable Energy Laboratory (NREL) defines a biorefinery process as "A facility that integrates biomass conversion processes and equipment to produce fuels, power and chemicals from biomass" (NREL,2014). According to International Energy Agency (IEA) biorefinery is "A sustainable process of converting the biomass into a range of marketable products and bioenergy" (IEATask42,Bioenergy, 2008).

Presently there are four known and practical categories of biorefinery processes. The first category, first-generation biorefinery, refers to biofuels production from agricultural biomass like corn, starch, vegetable oil and sugar cane. Although this type of biomass is rich in sugar and gives high production yield, the technology is controversial with regard to environmental and social aspects. Some risks are identified such as the risk of creating a competition between biomass for food consumption and the amount needed for the biorefinery. Furthermore, there are risks attributed to the consumption of fertilizers and pesticides and overexploitation of agricultural land (Demirbas, 2010).

The second-generation biorefinery is the process that mainly uses lignocellulosic biomass and is generally known as forest biorefinery. Similar to petroleum refineries, forest biorefinery involves the fractionation of feedstock into components that are used in chemical, biochemical or thermochemical processes. This can yield in products that can be further processed in different production platforms in order to be converted to higher added-value chemicals, energy, biofuels, etc. (Holladay et al., 2007). Unlike the first category, it improves the environmental balances, and the biomass does not compete with the human food consumption. Biomass in this category is so abundant that the purchase price is relatively low, leading to low production costs. However, some conversion technologies associated with this category are still under the process of research and development (Kamm et al., 2007).

The third generation consumes the aquatic biomass, such as algae. This category has advantages in process performance, but is mostly comparable to the first generation biorefinery, particularly in terms of economy and landuse. In addition, some processing technologies are still under development (Sheehan et al., 1998). The fourth generation uses vegetable oils and other types of municipal waste. It solves the common problem associated with the waste treatment and management and it has been used in an industrial scale (Demirbas, 2010).

1.1.1 Integrated forest biorefinery

Forest biorefinery is the most promising biorefinery concept for places where a well-developed forestry sector and particularly pulp and paper (P&P) industry exists. Due to the present economic challenges, it is essential for these companies to invest on the development of new strategies, based on sustainable bioproducts. Considering the potential strategies, forest biorefinery represents a great opportunity that fulfills the needs for solving the problems of forestry industry and facilitates the transformation of these companies (Wising and Stuart, 2006).

Transformational approaches are divided into two categories. The first approach emphasizes on tightly integration of the biorefinery processes and exchange of material with the P&P processes, which in turn requires a detailed review and evaluation of the existing and available resources at the mill. On the other hand, the second approach is related to building a new plant, preferably next to the existing mill facilities, that uses new sources of biomass, without interfering in the process of the existing plant (Browne et al., 2013). Examples of this approach are production of pellets or transportation biofuels from forest or agricultural based feedstock.

Regarding the first approach, different types of integration are defined for the forest biorefinery, including; process, infrastructure, feedstock and product, supply chain and policy and environmental integrations (Stuart and El-Halwagi, 2012). Process integration is based on detailed approach for design and operation of industrial processes and focuses mainly on mass and energy integration. By performing process integration, biorefineries can be designed for high-energy efficiency, efficient raw material utilization and low environmental emissions.

Infrastructure integration provides a link between biorefinery process and existing facilities at the P&P mills.

Forest biorefinery integration refers to an alternative for forestry companies wishing to implement retrofitting or retro-installation of biorefinery processes and technologies in an existing P&P mill. These mills have the required infrastructure for the biomass transformation into valuable products, energy and fuel. Such integration provides many advantages, including the use of the existing supply chain in terms of synergy of the raw material supply and distribution of finished products. In addition, the biorefinery process can benefit from the use of available resources like energy, biomass, water and chemicals at the mill. This approach inevitably leads to a significant reduction in costs of biorefinery implementation (Van Heiningen, 2006). From the environmental point of view, biorefinery integration can improve the plant efficiency, in terms of mass, energy and process debottlenecking. This in turn leads to the reduction of environmental emissions, particularly the overall greenhouse gas (GHG) emissions.

Significant advancements have been made by a number of researchers who have studied the concepts behind the integration of forest biorefinery processes. Several technology platforms are developed including hemicelluloses extraction from wood chips prior-to-pulping, lignin precipitation from black liquor, black liquor gasification for chemical recovery, electricity and bio-product production (Paleologou et al., 2011). In the following section, brief description of these technology platforms is presented.

1.1.2 Biorefinery conversion technologies

There are strong and tight interconnections of heterogeneous substances in the woody biomass that make this conversion process quite challenging. Biorefinery technologies are typically classified into biochemical and thermochemical conversion processes. The biochemical process is based on chemical fractionation of lignocellulosic biomass, whereas thermochemical process relies on gasification or pyrolysis of by-products and residues in the P&P mills (Sims et al., 2008). As potential biorefinery technology platforms, Wising and Stuart (Wising and Stuart, 2006) proved that hemicellulose extraction prior to pulping and lignin precipitation as biochemical pathways, and black liquor gasification or pyrolysis as thermochemical pathways have the potential to be integrated into the existing P&P mills.

1.1.2.1 Biochemical processing

Biochemical conversion refers to woody biomass breakdown for making the carbohydrates available for further processing. These carbohydrates are processed into sugars and lignin, which in turn can be converted into biofuels and biochemicals (USDOEnergy, 2009). Biochemical conversion operates at low temperature with relatively low reaction rates, resulting in higher selectivity for products. In this process, conversion of lignocellulosic material to bioproducts such as biofuels and biochemical is performed in a series of operational steps. The major unit operations in these processes include pretreatment, hydrolysis, fermentation and product separation and purification (Liu et al., 2012).

According to Mabee et al (Mabee et al., 2006), one of the advantages of this conversion process is the opportunity to create a biorefinery that produces value added biofuels and coproducts. For instance, sugars can be processed to produce a variety of products including ethanol, butanol, lactic acid, acetic acid, xylose, and so on. These products have the potential to be utilized as feed material for manufacturing jet fuel, plastics and specialty chemicals. However, biochemical conversion technology has some key challenges including considerable investment cost and the difficulties of fractionating the tough and complex structure of the cell walls in the lignocellulosic biomass. In addition, converting the resulting sugars into biofuels and purifying them is another challenge for this process (USDOEnergy, 2009). As the principal processing step, pretreatment plays a significant role in the successful operation of biochemical platforms. A summarized description of different pretreatment technologies is explained in section 1.1.3.

1.1.2.2 Thermochemical processing

Thermochemical conversion process is a technology that operates at elevated temperatures and it has two most common pathways including gasification and pyrolysis. Gasification is the process of converting organic materials at high temperatures and reducing conditions, to produce synthesis gas, char, water and considerable minor products. Whereas pyrolysis is a process related to thermal conversion of organic materials. Pyrolysis carries out in the absence of oxygen and at elevated temperatures; product in this process is liquid oil (Grabowski, 2008).

Due to the high operating temperatures (300-1000°C), natural resistance of lignocellulosic biomass to conversion can be overcome. Therefore, these processes, unlike biochemical conversion technologies, are less sensitive to the type of biomass. Thermochemical processes utilize a wide range of biomass feedstock that enables the production of various types of advanced biofuels including ethanol, butanol, gasoline, diesel and jet fuel. However, there are some key challenges associated with this conversion technology including: reliable reactor operation, the need for improved catalysts for the production of liquid fuels also for upgrading the bio-oils into other fuels, oxygen removal and cleaning and stabilizing the bio-oil (USDOEnergy, 2009).

1.1.3 Pretreatment processes

Graf and Koehler defined pretreatment as the first step in biochemical conversion of lignocellulosic biomass to biofuels and chemicals (Graf and Koehler, 2000). Pretreatment assists the physical disruption and fractionation of lignocellulosic matrix. Woody biomass is consisted of four major components: Cellulose, hemicellulose, lignin and extractives. Cellulose is most resistant to chemical, thermal and biological conversions. On the contrary, hemicellulose and extractives are less resistant to degradation processes (Liu et al., 2012).

Pretreatment is an important process step for practical lignocellulosic conversion processes and the goal is to alter or to remove the structural and compositional obstacles prior to hydrolysis and other processing stages. By performing the biomass pretreatment, hydrolysis rate can be improved, which in turn results in higher yields of fermentable sugars from cellulose and hemicellulose (Liu et al., 2013). An effective pretreatment is recognized by several parameters, including: preserving the hemicellulose or pentose fractions, limiting the formation of inhibitors and degradable products impairing the hydrolysis and fermentation processes, also preventing the requirement for the biomass particles size reduction (Feng, 2012). Various pretreatment methods have been developed including: Biological, physical or mechanical, chemical and physiochemical pretreatment (Balat, 2011). The choice of proper pretreatment method can have significant impact on the configuration and the efficiency of the biorefinery process and ultimately its economic performance (Mosier et al., 2005). In the following section, description of some pretreatment methods for the removal of hemicellulose component prior to pulping process is elaborated.

1.1.3.1 VPP process and Hot water extraction

One paradigm receiving attention from the industry is the concept of “value prior to pulping” (VPP) (ESF-VPP). Hemicellulose that makes up about 20 to 30% of woodchip feedstock in chemical pulp mills usually ends up in the black liquor stream and is burnt in the recovery cycle. VPP is the process of extracting hemicellulose from pulpwood prior to pulping by using hot water and other mediums, and under different operating conditions (temperature, pressure and residence time). Under certain conditions, the extraction of this component prior to pulping can be done without diminishing the fiber quality. The extracted hemicellulose from wood chips can be used in the production of added-value chemicals and biofuels as well as to improve the yield and quality of pulp (Van Heiningen, 2006). Additionally, if the recovery cycle in the pulp mill is a bottleneck, hemicellulose extraction will lead to some offloading in the recovery cycle. This process debottlenecking allows mills to increase their pulp production capacity, improves performance of pulping process, and results in economic profitability (Ghezzaz et al., 2012a).

Extensive research has been conducted for various hemicellulose pre-extraction processes on several wood species. These processes include alkaline, acid and hot water (also known as auto hydrolysis) extraction. Mao and Van Heiningen (Mao et al., 2008) performed profound studies on near-neutral hemicellulose pre-extraction process from hardwood chips. In this process, green liquor generated in the pulping recovery cycle is used as a solution with sufficient alkalinity to approximately neutralize the acids released during the pretreatment of wood chips at elevated temperatures, resulting in a final liquor with near-neutral pH. Under these mild alkaline conditions, xylan (a component of hemicellulose) released by the wood during the pre-treatment process is dissolved in the medium. This pre-treatment process preserves the pulping yield and pulp production rate. In addition, it results in off-loading in the recovery cycle, due to a reduction in the quantity of organics in the black liquor. Consequently, the amount of white liquor needed for pulping is decreased and pulp production capacity is increased. However, it is worth mentioning in the near-neutral pre-extraction process, the amount of extracted pentose sugars is low. Moreover, the extracted liquor contains inorganic salts that are generated from the green liquor.

Al-Dajani et al. (Al-Dajani and Tschirner, 2008) performed hemicellulose extraction from aspen wood chips under alkaline conditions and relatively low temperatures (50-90ºC). Under these operating conditions and by using sodium hydroxide, 40 to 50 kg of hemicellulose per metric ton of wood chips was extracted. Due to low operating temperatures, the process does not require costly pressurized vessels. In addition, they found that extraction could be performed without detrimentally affecting the pulp properties and decreasing the pulp yield.

Hot water extraction (HWE), as a well-proven pretreatment process, results in good recovery of all of the cellulose, hemicellulose and lignin components in a usable form. With this pretreatment method, the cellulosic component can be efficiently used in the pulp making process. The extracted stream, which mainly consists of hemicellulose, can be used as feedstock for various process alternatives. HWE is considered an auto hydrolysis process and is conducted under mild acidic conditions that catalyze the hydrolysis of wood constituents. It is an effective method for defibrillating plant cell walls; especially hardwoods and good hemicellulose sugar recovery can be performed after extraction (Amidon et al., 2008).

Amidon et al. (Amidon et al., 2008) considered HWE for the pre-treatment of sugar maple wood chips. The process consists of the fractionation of lignocellulosic biomass into its main components by sequential treatments to give separate streams that may be utilized in various applications. HWE of hardwood chips at 160°C during 2 hours removes approximately 23% of the woody biomass (mostly in the form of hemicellulose). They also observed that total mass removal from biomass increases with temperature and extraction time. Xylooligomers and acetic acid in the extracted stream were found to be the major components that have the greatest potential value for development. Currently, there is on-going research based on the enhancement of HWE with the production of furfural, nanocellulose and high value lignin.

In addition to the studies carried out to determine the functionality and impact of the VPP process on pulp products, several authors have also reviewed the economic aspects of the VPP process. Goyal et al. (Goyal, 2013) reviewed different VPP processes and compared their techno-economics. In a detailed case study, they considered the extraction process under acidic conditions. Prehydrolysis using acetic acid was selected as the means for hemicellulose extraction from hardwood and softwood chips. The process steps were: concentration, fermentation and distillation, with the objective of producing ethanol from extracted hemicellulose. The overall pulp yield from wood chips was decreased in this VPP process compared to un-extracted pulps. The results of the detailed techno-economic analysis for ethanol production proved that profitability can be negatively affected by a decrease in pulp yield, resulting in an increase of the total wood quantity required to produce the same amount of pulp. Moreover, the small scale of ethanol production from extracted wood mass, high investment costs for the ethanol plant and extraction steps that require large-sized equipment for pretreatment of whole wood chips prior to pulping had negative impacts on the economic results.

As previously explained, integration of a suitable biorefinery pretreatment process into an existing P&P mill brings improvements in the mill's process performance, also results in environmental and economic benefits. In the subsequent section, the concept of integrating a HWE pretreatment into a P&P mill is discussed.

1.1.3.2 Integrating a HWE-based biorefinery into a P&P mill

In a P&P mill, wood chips from round wood and/or residual wood chips and shavings from lumber mills are chemically or mechanically disintegrated into fibers (Das and Houtman, 2004). Depending on the wood type, softwood or hardwood, Xylan that is the main component in the hemicellulose contributes to 20-35% of the dry wood mass. In a regular pulping process, this component remains unused. Nonetheless, it is a valuable renewable resource that has a great potential for the production of bio-based fuels and chemicals (Amidon et al., 2011). As mentioned previously, in a HWE pretreatment, hemicellulose is easily separated from the woody biomass. At a certain level of extraction, not only removing hemicellulose does not affect the pulping material, but also the residual solid material contains fewer degradable components. This in turn provides a more efficient further processing to convert the remaining cellulose and lignin into traditional pulp products. Development of an alternative application for this valuable extracted hemicellulose (xylan) is of great importance. It justifies a potential starting point for integrating a sugar platform biorefinery into an existing pulp and paper mill. Figure 1-1 represents a schematic of the biorefinery that utilizes lignocellulosic biomass as the feedstock and is proposed by Amidon et al (Amidon et al., 2008). In this figure potential production pathways for the resulting products from the mill process and the biorefinery are shown as well.

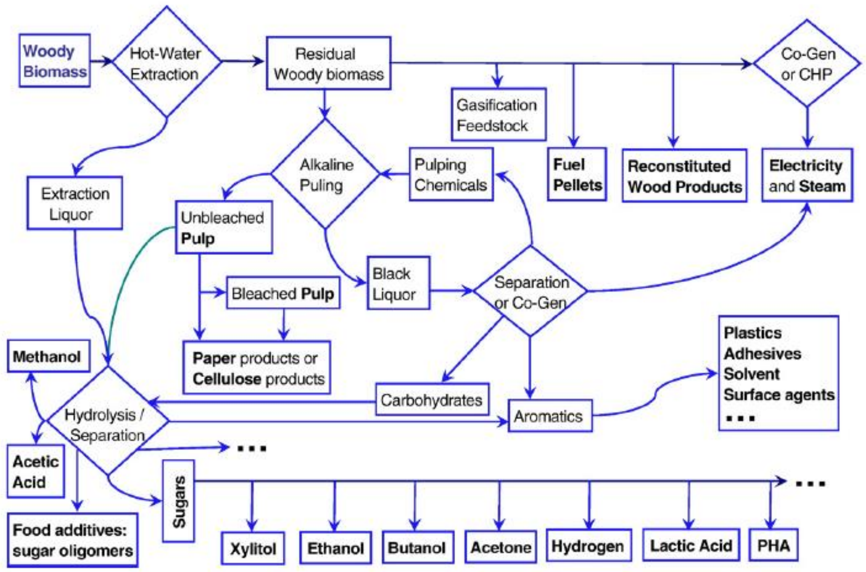

Figure 1-1 Schematic of an integrated HWE - based biorefinery (Amidon et al., 2008)

Major process stages in this biochemical platform include HWE pretreatment, hydrolysis of the extracted streams, separation of xylan, sugars and acetic acid, fermentation of sugars to ethanol or bioplastics and use of extracted wood chips for making traditional wood products.

As a successful application of HWE, American Process Inc. (API) has constructed a semi-commercial biorefinery based on HWE of hardwood chips in Alpena, Michigan. The derivative process from the Alpena project is Green Power+^{TM}. In this project, power and ethanol are co-produced, maximizing the value added products from biomass (APInc., 2011). API is making the process cost effective by using the extracted stream from hardwood and converting it to cellulosic ethanol and potassium acetate. In order to create a financially successful project, API has reduced the capital costs of the production of ethanol from hemicellulose and also by producing bioproducts, i.e. potassium acetate. To further improve the economic performance of the process, API has also considered switching from ethanol to butanol production as a main product.

1.1.3.3 Overview of potential products from extracted sugar stream

The extracted stream from HWE pretreatment comprises of monosaccharide, polysaccharides, acetic acid, aromatics or degraded lignin, and other low molecular weight extractable substances. Hemicellulose, as the major component in the stream is composed of hetro-polymers of five- and six-carbon sugars with short-branched side connections. There are several applications for the extracted components; particularly sugars are used as building blocks for several value-added products and chemicals that are currently produced from fossil-based resources (Amidon et al., 2008). As potential production pathways for the extracted C5-sugars; xylitol, furfural, levulinic acid and butanol are proposed (Werpy et al., 2004). Depending on the wood species, operating conditions of the pretreatment unit and the type of pulping process, the extracted sugar has different chemical properties (Ragauskas et al., 2006).

In hardwood mills, xylan in the extracted stream is concentrated and then hydrolyzed to produce xylose. Xylose from this process can be sold to the market without any further processing and modification. There are numerous producers located in Asia who play a large role in the current market and the global market size for C5-sugars is predicted to be 200,000 tons/year. The price volatility is attributed to the periodic overproduction of Chinese producers (Mao et al., 2008). Alternatively, xylose is converted to high-value added products for instance furfural and xylitol.

Xylitol as a five-carbon sugar alcohol has potential to be used as a natural food sweetener, a dental caries reducer and a sugar substitute for diabetics (Saha and Bothast, 1997). As a sustainable and natural sweetener it has the same sweetness as sugar but with 40% less calories. The bulk of xylitol is consumed in various food products such as chewing gum, candy, soft drinks, and ice cream (Schoenhals, 2003). However, the xylitol production process requires high pressure (up to 50 atm.) and high temperature. Other technological limitations are related to the application of expensive catalysts and the use of extensive separation and purification steps for removing the by-products (Saha and Bothast, 1997). In addition, with the commercial production of xylitol outside China being limited, the product market becomes challenging (Jong et al., 2012).

Alternatively xylose can be dehydrated to produce furfural. Furfural as one member of furanics class, consists of a group of molecules including 5-hydroxymethylfurfural, 2,5-furandicarboxylic acid and 2,5-dimethylfuran. It is an established chemical product with a static market. The largest current producers of furfural are located in Dominican Republic and China; with a strong competition coming from Chinese producers. The global market is estimated to be over 250,000 tons/year and to be growing further to 350,000 tons/year in 2020 (Win, 2005).

Butanol is regarded as an alternative product from the extracted hemicellulose. It has the potential to be used as a drop-in biofuel, also having some applications in the chemical production market. Nonetheless the stream from the fermentation step of butanol production is extremely diluted, and increases the steam and energy demand for sugar sterilization and the product recovery through distillation (Mariano et al., 2013). Goyal et al. (Goyal, 2013) analyzed the techno-economics of the butanol production. They found that the application of butanol as a chemical resulted in better economic performance than butanol as a biofuel.

On the other hand, in softwood mills, the extracted hemicellulose is hydrolyzed to C5- and C6-carbon sugar monomers. C5-sugars are converted to the same products as in hardwood mills. In addition, hemicellulose that is rich in C6-sugars can be fermented to ethanol (Saha et al., 1998). However, the small scale of ethanol production from extracted wood mass, high investment costs for the ethanol plant and extraction steps that require large-sized equipment for pretreatment of whole wood chips prior to pulping had negative impacts on the economic results and profitability.

1.1.4 Critical analysis

Selection of proper biorefinery conversion technology, pretreatment method and production pathways are quite important in the forest biorefinery integration. Numerous pretreatment methods that can be integrated into a P&P mill exist, each of them have particular specifications also operational challenges. The ultimate objective is the efficient fractionation of lignocellulosic material into multiple streams that contain value-added compounds, without threatening the fiber and pulp quality. Another parameter that has to be taken into account while choosing a pretreatment process is the quantity and concentration of the resulting streams that makes the purification and product recovery economically feasible. Therefore, detailed economic analysis and process evaluation through experimental data are required to determine the most proper pretreatment process option for a specific feedstock and product opportunity. Additionally, resource utilization between the biorefinery plant and the P&P mill should be evaluated deliberately and at the early design stages. Development of alternative applications for the valuable extracted streams is of great importance and becomes a critical decision. By moving to more added-value products, techno-economic results will be ameliorated and there will be an increase in the return on investment.

1.2 Sustainable development

The concept of sustainability has evolved in recent years. Brundtland provided the standard definition of sustainable development as “A development that meets present needs without compromising the ability of future generations to meet their own needs” (Bruntland, 1987). Devuyst et al (Devuyst et al., 2001) defined sustainability assessment as a tool that can help decision-makers and policy-makers decide which actions they should or should not take, in an attempt to make society more sustainable. Although these concepts are generally accepted, there are worldwide differences in the interpretation and application of sustainability. Sustainability and sustainable development are used interchangeably to refer to the maintenance of a resource or a system over time (Diaz-Chavez, 2011).

Traditionally, the context of sustainability relies on three pillars; environmental, economic and social. The sustainability issues that should be addressed when evaluating systems, projects or products include but are not limited to the following:

- Environmental impacts like global warming, acidification, biodiversity, land use change
- Economic aspect for instance investment cost and profitability
- Social parameters such as employment and human health

Aside from the three above-mentioned aspects that are usually regarded in the sustainability evaluations, risk parameters or uncertainty sources is an important aspect that has to be taken into account and is described in section 1.3. In recent years, sustainability concept has become very dominant in industrial projects especially in fields that are related to renewable resources like forest biorefineries. Decision-makers and investors are paying considerable attention to the sustainability performance of a given biorefinery project, prior to embarking on any investment. The following section reviews the sustainability performance of forest biorefinery processes.

1.2.1 Sustainability evaluation of forest biorefinery processes

To sustain the present way of life, conversion of biomass into chemicals and energy is essential. Fossil fuels as the dominant energy supplies have limited and non-renewable resources; on the contrary, biomass is regarded as a reliable source that can be re-produced. The main objective of implementing a biorefinery project is to develop sustainable sources of renewable energy and products that can displace fossil fuels and fossil-based products, increase energy security, promote environmental benefits and create economic opportunities (IEATask42,Bioenergy, 2008).

Forest biorefinery processes are playing a significant role to achieve the sustainable development goals by having substantial economic, environmental and social effects that provides promising opportunities (Batsy et al., 2013). However, moving towards sustainability requires reconsidering of the design of production systems, product consumption and waste management (von Blottnitz and Curran, 2007). Therefore, economic and environmental evaluations of different biorefinery implementation options are of great importance in optimizing the use of resources and reducing the related environmental impacts.

Economic sustainability of a biorefinery project can be ensured through monitoring and forecasting the investment costs, profitability, productivity and efficiency across the entire supply chain and for multiple feedstock and production pathways (USDOEnergy, 2009). Environmental sustainability implies a commitment to continuous improvement in the environmental performance. Biorefinery offers a significant potential to mitigate climate change by reducing lifecycle GHG emissions, relative to competitive fossil-based products. Although producing biomass-based products releases carbon dioxide, biomass absorbs carbon dioxide from the atmosphere as it grows. On the contrary, fossil-based products release carbon that has been sequestered for a long period of time, resulting in a net positive increase in the atmospheric carbon (Liu et al., 2012).

There are few sources in the literature that address the social aspect of sustainability. However, some models and methodologies are developed by economists to measure the economic impacts of biorefinery implementation. One technique used for this purpose is called input-output modelling (Harris and Liu, 1998) and it is related to the mathematical relations between the economy and the impacts on different regional sectors. In addition, modelling software called IMPLAN is developed by Minnesota IMPLAN Group (Mulkey and Hodges, 2004) which provides a regional economic impact assessment model. This model analyzes the way that spending associated with biorefinery implementation circulates through an economy of a study area. Different impact layers are identified using this model including: output that represents the value of bioproducts which is the generic measure of economic activity, personal income or labor income that consists of employee compensation, proprietary income and jobs creation including full-time and part-time employment.

Many studies are performed to identify a systematic methodology for the sustainability evaluation of forest biorefineries. Hämäläinen et al. (Hämäläinen et al., 2011) conducted a Delphi study (Hsu and Sandford, 2007) in three layers including macro-scale, industry and strategic to identify the major parameters that should be considered in the biorefinery implementation. They realized that the most dominant drivers at the macro-scale are the long-term policies, security of fuel supply and high price of oil. At the industry level, successful implementation of biorefinery by efficient utilization of wood as the biomass resource, availability of financing and collaboration between different players of the value chain were identified. Ultimately at the strategic level, identification of the new markets, change management and economic development of biorefinery technologies were realized as important factors.

Buytaert et al. (Buytaert et al., 2011) examined the potential usefulness and applicability of some existing tools for the sustainability evaluation of bioenergy systems. They employed LCA, EIA, criteria and indicators; cost benefit, exergy and system perturbation analysis in their assessment. A framework was defined and a statistical analysis was performed to identify the major differences between tools. For this evaluation literature review and a Delphi panel of experts were used. The results proved that each tool has its own advantages and disadvantages. Due to the unique characteristics of these tools, none of them were adequate to perform a comprehensive sustainability evaluation of bioenergy projects. Therefore, it became evident that a systematic assessment methodology is needed to incorporate all the necessary tools for the decision-making purposes. Sharma et al. (Sharma et al., 2011) formulated and implemented a model to design the technology and product portfolio for a multi-product biorefinery strategy. They evaluated the influence of stakeholders and process integration on the profitability and sustainability evaluation.

Regarding the biomass that is used in the forest biorefinery, countries like Canada with large volumes of forestry-based biomass present great opportunities for emerging biorefinery technologies. These countries contribute to clean and new economic development (Paleologou et al., 2011). However, it should be noted that the sustainability of the woody biomass depends on several factors. Sustainable forest management is a critical issue that should be considered.

Particularly, feedstock harvesting is a great challenge in the value chain contributing to sever environmental impacts (Liu et al., 2012).

Although in many cases, biorefinery implementation illustrates considerable economic opportunities and environmental improvements; there are risks and uncertainties associated with these projects that should be considered as well. It should be realize that completing a checklist of environmental, economic and social parameters does not necessarily contribute to the sustainability of a biorefinery project. Practical assessment methodology that takes into account potential risks is required before embarking on the development of a forest biorefinery process and making any investment. Different types of risks in the context of biorefinery processes and potential mitigation strategies described in section 1.3.

1.2.2 Critical analysis

As the biorefinery technologies are continuing to progress, there is a growing demand to have practical-realistic definition and evaluation method of all the parameters that may have potential impacts on the biorefinery accomplishment. When addressing the sustainability assessment of an integrated forest biorefinery, following questions should respond:

- Which type of lignocellulosic feedstock is proper to use in the pretreatment and further processing stages without having adverse effect on the main pulping line and on the biorefinery process?
- Which conversion technology should be selected; thermochemical or biochemical?
- What can be the potential mass and energy impacts due to the biorefinery integration on the core-process of the pulp and paper mill?
- What is the technology risk attributed to the defined bio-pathway?
- What are the best bioproduct pathways, which added-value co-products should be focused on?
- What is the market pull for the candidate bioproducts? What are the potential risks?
- What can be the effects on the land use change, GHG, soil quality and biodiversity?

- How can financial risk associated with the project be mitigated? Is there going to be any incentive from the government or not?
- Most importantly, what is the best implementation strategy that encompasses the project profitability while mitigating the potential risks?

If bioproduction pathways are developed carefully, they can be the foundation of a more sustainable future.

1.3 Risk analysis in process design

Risk analysis is conducted to better analyze and understand possible impacts of variations in the business model. There are several qualitative and quantitative methods for incorporating the uncertainties into the techno-economic analysis. Different methods of risk assessment include qualitative risk analysis, quantitative risk assessment and Multi-Criteria Decision Making (MCDM).

The qualitative method is applied in strategic planning for traditional process design activities and is suitable for investment strategies or project risk evaluation at the early stage of decision-making process. Structured planning methods like SWOT (Strength, Weakness, Opportunities and Threats evaluation) and PEST (Political, Economic, Social, and Technological) are applied within this method. In this approach, each uncertain parameter is verbally quantified to reach to an overall benefit-disadvantage description of the defined scenarios. It is important to highlight that the quantification step under the qualitative conditions is performed subjectively (Hytönen and Stuart, 2012).

In the quantitative risk assessment approach, deterministic or stochastic methods can be executed. A deterministic risk analysis has two methods and uses techno-economic models. In the first approach, uncertainties are identified with the same level of probability, which are then propagated into output results. An example of this method is sensitivity analysis, where ranges for minimum and maximum values are defined for uncertain parameters (Hytönen and Stuart, 2012). In the second method that is also referred to as scenario analysis, some aspects of the system are regarded as uncertain parts. Uncertainties are evaluated subjectively by employing verbal or ordinal scales to represent their probability magnitude. In the arbitrary nature of this method, which can rely on the experience and knowledge about a given context, uncertain parameters are quantified and transformed into some values and results (Schoemaker, 1995). The principles of this analysis are relatively the same as sensitivity analysis and it is mainly intended to capture the idea of risk mitigation and strategic planning. The main weakness of this approach is the same as sensitivity analysis, in both approaches the probability of the scenarios are not defined systematically. In the stochastic method, quantification of uncertain variables is performed, using their probability distribution (Hytönen and Stuart, 2012).

MCDM framework, as a systematic analysis tool, is used to make decisions to solve problems that involve conflicting issues of different perspectives. To make a balanced and well-informed decision, different criteria are considered and the decision criteria are the results of various system analyses. The criteria to be used in MCDM represent technology, market and core business risks and are calculated either qualitatively or quantitatively. The decision panel includes stakeholders with knowledge related to the specific field. MCDM helps them to systematically prioritize their preferences and the relative importance of the criteria in order to make sustainable decisions (Janssen et al., 2010).

1.3.1 Risks in the context of biorefinery processes

It is vital to perform the risk assessment in the retrofit design of biorefinery projects. In this context both new biorefinery and traditional technology alternatives exist. Evidently, the new retrofit biorefinery technology has higher level of risk, when compared with the traditional alternative, for instance a P&P mill. The critical task in risk analysis is to identify the types and the sources of uncertainties. There are different sources of uncertainties in the biorefinery design (Pistikopoulos, 1995):

- Process-inherent uncertainties such as process yield, temperature variations, etc. that are critical especially for emerging, new biorefinery technologies.
- Market volatility: This includes feedstock availability and price; as well as product demand, selling price and quality.
- Process integration uncertainties due to insufficient knowledge at unit operations and business level for scale-up of laboratory or pilot scale processes. Also energy integration uncertainties and risks related to core business.

- Discrete uncertainties such as government policies, technology and product subsidies and available project financing, which are uncertain especially in the context of biorefinery processes.

1.3.1.1 Risks to the core business

Prior to considering any biorefinery strategy and making any decision, pulp and paper companies need to be assured that biorefinery implementation has little or no risk to their core business. In addition, the majority of forestry companies will furthermore insist that through the implementation of the biorefinery, operating costs related to the core business will be reduced. As for the risks to the mill's core business, it is vital to perform a systematic evaluation on how retrofitting a biorefinery technology might impact the main pulping line, pulp quality and resources utilization (energy system, wastewater treatment and available biomass quantities at the mill).

Many studies have been carried out to identify process integration risks. For instance Ghezzaz et al. (Ghezzaz et al., 2012a) performed a systematic risk assessment on the impacts of integrating two biorefinery technologies on the process of a soda P&P mill (the same mill as this case study). The evaluated biorefinery technologies were near-neutral hemicellulose pre-extraction and lignin precipitation from black liquor by acidification with carbon dioxide (CO_2). The results of their analysis regarding the risks associated with the second technology proved that the use of CO_2 as an acidification agent in a soda-mill was uncertain. Since, CO_2 leads to a weak acid in contact with water, the precipitation has to be done under high pressure of CO_2 in order to reach the pH level leading to the desired outcome. For the first technology, pulp quality was observed to be the main potential risk since there was no available data related to the impact of hemicellulose extraction on the quality and properties of high yield soda pulps. In addition, implementing this process increased the energy demand, due to additional required energy in the extraction step as well as products separation and purification (Ghezzaz et al., 2012a). Result analysis showed that the economic opportunities of implementing these two biorefinery technologies were significant. However, neither of these processes was suitable enough for the biorefinery integration, due to the risks they might cause to the P&P mill's core business (Ghezzaz et al., 2012b).

It is important to highlight that integrating a HWE-based biorefinery into a mill might affect the pulp quality. Especially at high hemicellulose extraction rates, there is a potential risk of losing pulp quality and deteriorating the pulp mechanical strength. Several authors have explored different combinations of temperature, pressure and extraction time. In the analysis performed to determine the effect of HWE on softwood and hardwood chips, Van-Heiningen et al. (Yoon and Van Heiningen, 2008) found that for loblolly pine kraft pulps, HWE pretreatment caused slower refining response and lowered tensile strength due to the lower percentage of hemicellulose within the fibers, when compared to un-pretreated pulps. However, the pretreated kraft pulps showed comparable viscosity and tear resistance. In the analysis of hardwood chips, Amidon et al. (Amidon et al., 2011) ascertained that hot water pretreated chips have better bleaching properties. Also, it has been shown that by using an HWE-based biorefinery process, risks associated with the recovery cycle can be reduced and this represents a significant cost reduction opportunity for the mill. Nonetheless, it is important to optimize the cooking conditions and hemicellulose extraction rate, to minimize the degradation effects and to reach satisfactory pulp strength properties (Duarte et al., 2012).

1.3.1.2 Technology risks

Emerging biorefinery technologies are in various phases of their development and are operating at different production scales. Larger facilities are more costly and more difficult for industries to develop. Due to the relative immaturity of available biorefining technologies, few of them are planned for the near future (Mabee et al., 2006). The choice of a suitable technology at the early design stage is a challenging task due to scarce and uncertain information available from technology developers, as well as the ambiguity of the particular context and risks involved in implementing the biorefinery (Cohen et al., 2010).

Technological parameters that are needed to consider are summarized into: flexibility to use different types of feedstock, process and manufacturing flexibility, successful scale-up opportunities from pilot to commercial scale plants and operational robustness (Demirbas, 2009). Technology risk mainly addresses process scale-up complexity, as a function of the number of process units (in each production line), and current process scale versus the targeted scale. Even the near-commercial scale biorefinery technologies have a substantially higher level of risk when compared to the mature technologies that have already been implemented in the core business of P&P companies.

Cohen et al. (Cohen et al., 2010) reviewed selected emerging technologies for ethanol production in an integrated forest biorefinery framework. The objective was to evaluate the risks at each unit operation. Key technology issues such as process efficiency, costs and process design-related information such as feedstock flexibility were considered in their analysis, as well. Phase I Implementation Capability (PIC) is a criterion presented by Sanaei et al. (Sanaei and Stuart, 2014). It is an aggregated measure of technology risk that represents the level of technology maturity, scale-up requirement to commercial scale and ability to execute the Phase I product-process combination. Higher value of this criterion presents a lower technology risk in Phase I and an opportunity to be faster to the market in Phase II.

1.3.1.3 Market risks

The transformation of P&P mills into biorefineries leads to market risks associated with selling new bioproducts to the market. In order to improve the business performance and to have a successful biorefinery business strategy, it is necessary to have a complete understanding of the market challenges at the early design stages (Chambost et al., 2007).

Market risk essentially covers market size, market growth, competition and product transportation (Chambost and Stuart, 2009). Market size determines how easy it will be for a given plant to find downstream markets for their products. Large markets tend to facilitate the selling of the products, but strong competition for market penetration will be a factor. On the other hand, small and undeveloped markets make it difficult to find stable and reliable downstream customers; however, they present a great opportunity for the company to establish its products within that market. Market growth is also important since it will drive local and global demand for the biorefinery products. Another risk parameter that has to be taken into account is the product transportation. If the plant is located far away from potential consumers, the costs related to product transport and distribution will increase significantly.

Within the context of the forest biorefinery, Chambost et al. (Chambost and Stuart, 2009) defined a step-wise methodology that focuses on value maximization throughout the biorefinery product portfolio. This methodology consists of 4 major steps;

1. For each individual product aiming to penetrate the existing value chain, a proper market strategy has to be characterized and assessed.

2. For each product family, value through the sale has to be created.

3. For the purpose of selling the product portfolio, a unique supply chain has to be defined.

4. To mitigate the market risks and improve the product positioning in the market, a winning partnership has to be identified.

1.3.1.4 Phased approach implementation

It is evident that a complete transformation of pulp mills into integrated forest biorefineries must be achieved incrementally over the coming years. Using a strategic phased approach that considers both short- and long-term visions is critical to enable risk mitigation and to achieve long-term goals. Chambost et al. (Chambost et al., 2008) introduced a three-phased approach for the purpose of successful P&P mill transformation into a biorefinery. Phase I and II deal with technological transformation by integration of biorefinery technologies while phase III involves business transformation by modifying the business approach of a company. In this phased approach, the emphasis is on the long-term product portfolio of the biorefinery. Defining the phases should begin with the design of phase III and based on the results of this phase, the previous phases are designed with the effort to mitigate the risk. (See Figure 1-2)

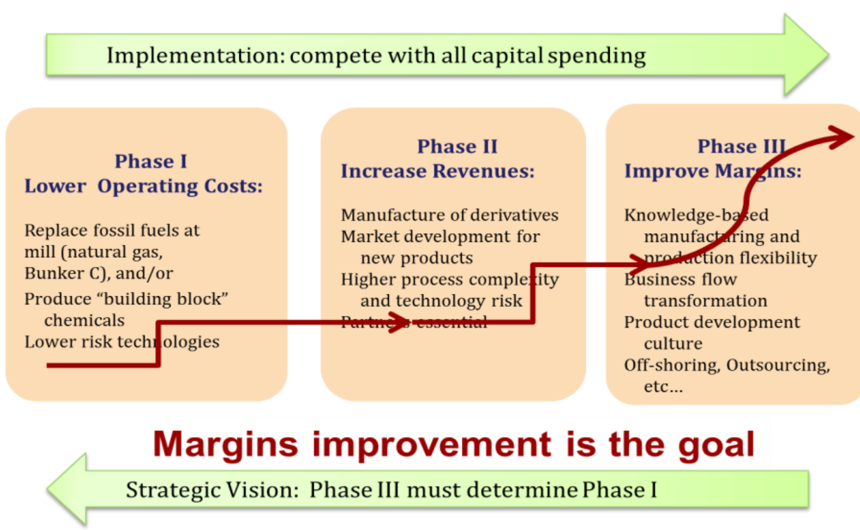

Figure 1-2 Strategic phased implementation of the forest biorefinery (Chambost et al., 2008)

Reducing the operating costs is the main objective of phase I. Also, to minimize the technology and the market risks, it is recommended to produce bioproducts that can be used internally, or the building blocks that can be sold for production of derivatives. Phase I is regarded as an intermediate step to phase II and at the proper time, phase II investments are made. Phase II represents the long-term vision of the company and intends to create value by the production of high value products. Suitable market analyses in terms of market penetration strategies along with gradual development of the product portfolio are essential parameters to be considered in this phase. In addition, partnership plays an important role to minimize the technical and financial risks. In order to have flexibility in strategies, phase II products can be used in more than one application. Phase III aims to maximize the margins and to improve the ultimate results. Manufacturing flexibility, supply-chain re-design and new delivery mechanisms are considered in this phase. Table 1-1 presents the level of risk and the implied business and technology strategies. The objective of both strategies is to mitigate risk and to create and maximize product value.

Table 1-1 Characterisation of the phase implementation

Characteristic	Phase II	Phase I
Implementation	Longer term	Near term
Technology risk	Higher, to be implemented in a few years' time	Relatively low, subsidy by government is necessary
Market risk	Higher risk, high return	Low (near zero)
Volumes	Added-value/specialty	Commodity
Integration risk	Minimal, assuming the added-value products are derivatives	Critical, ideally will reduce the cost of core business
Timing to market	Critical/First, early to market	Less critical

1.3.2 Critical analysis

As previously explained, there are several challenges related to biorefinery implementation. These risks include but are not limited to market and economic viability, technology maturity and manufacturing robustness. Even though biorefinery technologies are not new, there exist various challenges of process flexibility, stability and operational robustness associated with these processes.

In the context of forest biorefinery integration, forestry companies are recommended to consider incremental project implementation and using a phased approach. This strategy will enable these companies to mitigate market and technology risks attributed to the biorefinery technologies. Furthermore, phased implementation assists P&P companies to incrementally transform their business model to achieve short- and long-term strategic objectives.

1.4 Techno-economic analysis

Techno-economic assessment is required at different levels of the process design to provide reliable decision-making information for the project investors. Economic performance is an important criterion in strategic decision making for biorefinery processes (Hytönen and Stuart, 2012). Two main costs that are usually evaluated are operating and capital costs. In the assessment of these costs, mass and energy balances also the process conditions are used as the basis.

1.4.1 Operating cost analysis

Variable operating (production) costs encompasses all the costs related to raw material, energy, water and chemicals. These costs are estimated using the information from the existing mill and their monthly inventories, purchasing information of material and other available sources for similar facilities (Hytönen and Stuart, 2012). Variable costs are evaluated based the developed mass and energy balances. On the other hand, fixed operating costs including labour, maintenance, operating supplies, insurance, overhead, etc. are estimated based on the context of the study and information regarding the operational requirements. To calculate fixed costs, factors including fractions of the capital investment costs, total revenue or total operating costs are considered. In addition, depreciation of the invested capital is calculated employing the capital investment costs and a proper depreciation model, for instance linear or accelerated models. Taxes are calculated as part of the cash flow analysis as well. All these parameters are regarded as the operating costs (Dimian et al., 2003).

1.4.2 Investment cost analysis

Prior to constructing a plant, a considerable amount of money should be spent to buy a land for the facility and different process equipment, also to cover the expenses for engineering design and construction activities. All these necessary investments are categorized as fixed capital costs. Operational costs, first fills and commissioning expenses are regarded as the working capitals. Total investment cost is the sum of these two major costs (Turton et al., 2008). Different process design phases have their own standard capital cost estimation methods that are described in engineering references for example in Peters and Timmerhaus (Timmerhaus and Peters, 2004).

Equipment costs are usually estimated using the information from the vendors of each process unit also available references like NREL reports. Parameters including equipment capacity (from mass and energy balances), installations costs, and material factors for some especial equipment like pressure vessels are considered in the equipment cost analysis, as well. Indices for instance Marshall and swift cost or chemical engineering indexes are used to evaluate the cost of the equipment or process unit to be installed in the new production facility and at the time of installation (Timmerhaus and Peters, 2004). Equation 1-1 shows the basis of equipment costs calculations that are proper in the context of conceptual design. This equation can be applied to calculate the capital investment at the whole plant level and also at detailed single unit cost estimations.

$$\boldsymbol{C = C_{ref}\left[\frac{M}{M_{ref}}\right]^{a}\left[\frac{I}{I_{ref}}\right]} \qquad [1\text{-}1]$$

In this equation C refers to the cost of the new equipment, M the capacity of the new equipment, the capacity exponent, I the cost index and ref subscript is the reference related values (Timmerhaus and Peters, 2004). The next step is to sum up the single unit costs to estimate the total purchased equipment cost. This cost should be multiplied by a proper installation factor to calculate the total installed cost. In addition, in the capital cost analysis, a contingency factor is considered to represent the unexpected additional costs that have to be foreseen in order to obtain the total capital investment of a given project.

1.4.3 Profitability analysis

In process design, project profitability is regarded as the major indicator of the economic performance (Hytönen and Stuart, 2012). The existing economic performance indicators are categorized as traditional and modern measures. Returns on Investment (ROI), payback period and turnover ratio are the traditional indices. Net present value (NPV), discounted cash flow and internal rate of return (IRR) are regarded as the modern measures (Dimian et al., 2003).

1.4.4 Techno-economics of biorefinery processes

Integrated biorefinery projects can be designed in various ways depending on the feedstock type, process technology, and product portfolio also the case study P&P mill (Mansoornejad et al., 2010). In the biorefinery processes, feedstock, energy, capital cost and product revenue are the key contributors in the economic evaluations. Feedstock costs vary depending on their type and location. Agricultural residues and wood wastes have lower costs compared to other bio-resources. On the contrary, woodchips are usually at the upper end of the price range (Menon and Rao, 2012). Competition over the same biomass can cause an increase in its unit price, whereas, development and modifications in the harvesting methods and biomass processing may decrease the feedstock price (Huang et al., 2009). Therefore, raw material cost plays a significant role in the profitability of the biorefinery projects.

Integrating a biorefinery project into an existing facility, for instance a P&P mill, is regarded as a more cost effective way, compared with stand-alone projects (Andersson, 2013). Generally, biorefinery projects are capital cost intensive. Great capital cost savings can be predicted due to the employment of the existing facilities, utility systems and infrastructure (Hytönen and Stuart, 2009). In addition, detailed evaluation of the available resources, supply chain facilities and even existing manpower can result in great reduction in the operating costs of the biorefinery project. For example, in some retrofit biorefinery projects, there might be some decrease in the operating expenses with regard to labour costs, due to changes on the main P&P process and retirement of some parts of the plant.

1.4.4.1 Biorefinery projects financing, the role of government subsidy

There are several parameters that can significantly contribute to the success of a biorefinery project, among which; the role of financing and government subsidies is unquestionable. Supportive government policies are essential for the development of bioproduct and biofuels projects. Beneficial measures and incentives include but are not limited to loan and grant programs, tax credits and tax exemptions. Particularly for well-proven technologies, governments are recommended to put in place some encouraging policies to promote private sector investments on commercial scale projects. Also, production incentives should be considered for scaling up the pilot-scale biorefinery projects to demonstration and commercial scales (Gadonneix et al., 2010).

Especially for low-capital cost biorefinery projects, the impact of government subsidy on the economic profitability and internal rate of return is magnificent. This in turn, implies the subsidy's role to mitigate the financial risks associated with the biorefinery technologies.

1.4.5 Critical analysis

It is not simple to compare the investment costs of biorefinery projects, due to alternative process design pathways. In addition, early-stage techno-economic analysis of biorefinery processes is usually based on publically available information and also data from the technology providers. However, having access to the detailed data and reliable information related to biorefinery processes and products is often challenging. In addition, capital costs of the biorefinery projects are not certain since presently few commercial biorefinery plants have been constructed and most of the capital estimates are based on relatively similar industrial. All these uncertainties should be considered in a systematic manner in the early-stage decision-making.

Furthermore, government's policies including subsidies and incentives can contribute to drastic impacts on financial performance of the biorefinery projects and can change the investment landscape to a great extent. However, due to the limited financial sources for the technology providers and project investors, being first to the ground is very important.

1.5 Environmental analysis

An important driver for the development of biorefinery processes is the relative improvement in environmental performance of bio-products, comparing to products that already exist in the market. Various approaches have been developed to perform the environmental evaluation of the biorefinery processes: Environmental Impact Assessment (EIA), Regulatory requirements for the estimation of the process emissions, Best Available Technology (BAT) Analysis (James, 2010) and Life Cycle Assessment (LCA). LCA that uses a whole life cycle perspective is preferable to evaluate the sustainability of a given process, product or technology. The holistic environmental approach that LCA provides on products has made it valuable for environmental management in industry and environmental policy-making in government (Baumann and Tillman, 2004). By considering impacts throughout the product life cycle, from "cradle to grave", LCA provides a comprehensive view of the environmental trade-offs for different biorefinery processes. Moreover, by interpreting the results of the evaluations, LCA can be employed to help decision-makers with making more informed decisions (Curran, 2006). Also, EIA, regulatory evaluation and BAT approaches are project-site-specific and near-term, whereas, LCA is generally a site-generic and strategic long-term approach. LCA is considered as a promising tool in assessing the environmental sustainability of technological options due to its capability to evaluate the potential effects on the ecosystem, also on population and human health that might endanger the current and future generations (Dewulf and Van Langenhove, 2002).

Figure 1-3 illustrates the standard framework of LCA methodology. LCA has four steps, goal and scope definition, inventory analysis, impact assessment and interpretation (Baumann and Tillman, 2004).

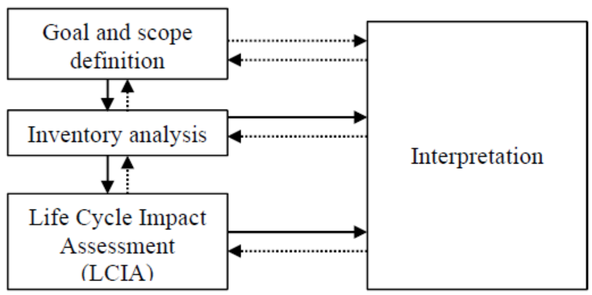

Figure 1-3 Main steps in the standard LCA framework (Baumann and Tillman, 2004)

Biorefineries are strategic projects. Therefore, environmental assessment tools must consider their long-term performance. LCA is generally an accepted approach for evaluating the environmental preference of biorefinery products. For the biorefinery projects, LCA can be used to evaluate replacing fossil-based products and fuels by bioproducts.

1.5.1 Consequential LCA methodology

The production of most renewable materials involves co-products; In order to model multi-output processes, LCA has a range of possible choices. Each allocation method has its own advantages and disadvantages and their application depends on the specific goal of the study (Weidema, 2000). Weidema describes the consequential LCA methodology as a method that is used to illustrate the consequences of a decision, also to evaluate the relations within the product value chain and between this chain and the surrounding technological systems (Weidema, 2003). According to Zamagni et al. (Zamagni et al., 2012), this approach is defined for a given point in time, at which, all the environmental changes are modelled in a steady-state way.

Consequential LCA is often used with system boundary expansion. System expansion considers the alternative products that are displaced when the co-product from the system under study is produced, and then credits the avoided impacts to the system. This combination is regarded to be the preferred approach while avoiding allocation; nevertheless, it leads to a more complicated model that requires more data (Curran, 2007).

In particular, consequential LCA methodology is used to evaluate the environmental performance of the integrated biorefineries (SANAEI et al., 2012). In this context, consequential LCA analysis can highlight the motivation to replace the fossil-based products by bioproducts, while evaluating the incremental environmental impacts from biorefinery integration. In addition in the context of decision-making, it can be used to evaluate several biorefinery strategies.

1.5.2 Life cycle assessment of biorefinery processes

Several authors have explored implementation of the LCA methodology in environmental assessment of the biorefinery projects. Mu et al. (Mu et al., 2010) compared the environmental performance of the two primary lignocellulosic ethanol production pathways, including biochemical and thermochemical conversions. The results of his analysis proved that in the near term, biochemical conversion would have better performance on GHG emissions and non-renewable resources. In an alternative integrated biorefinery analysis, Contreras et al. (Contreras et al., 2009) performed LCA on the by-products of sugar cane production. They defined four alternative product implementation strategies, using the by-product stream of the sugar production process. They analyzed the environmental impacts of the defined options and based on their results, the major impacts common between all the four alternatives were the land use change and respiratory inorganics. Neupane et al. (Neupane et al., 2013) completed an in-depth analysis of GHG emissions and resource consumption across the whole supply chain of wood-derived bioethanol, using the near-neutral hemicellulose extraction technology. The focus of their study was on the assessment of energy consumption and they found that lignocellulosic ethanol production under the near-neutral pretreatment condition demonstrated higher environmental performance, when compared with fossil-based fuels or even corn ethanol. Lim and Lee (Lim and Lee, 2011) implemented the consequential LCA approach to analyze the environmental consequences of the production of second-generation biofuels, bioethanol from palm oil biomass, compared to existing palm oil bio-diesel production.

The detailed LCA approach has been extensively-applied by the systems analysis research team at École Polytechnique de Montreal (Canada), including specifically for evaluation of biorefinery process-product options. Gaudreault et al. (Gaudreault et al., 2007b,2007a) reviewed the life cycle application in the pulp and paper industry and identified opportunities for improvement of LCA methodologies, using consequential analysis. They compared the information provided by attributional and consequential LCA approaches for decision-making in order to select the best process option, which leaded to less dependence of the mill on purchased electricity. Liard et al. (Liard, 2011) studied the environmental assessment of a Triticale-based biorefinery using LCA. They carried out Multi-Criteria Decision-Making (MCDM) studies to identify the most representative, comprehensive and interpretable environmental criteria, along with technical, economic and commercial criteria. More recently, Batsy (D.Batsy, thesis in progress) performed the environmental impact assessment of forest biorefinery product portfolio using a comprehensive LCA analysis. He implemented the consequential LCA and cut-off procedure in his LCA framework. Furthermore, he conducted an MCDM-based assessment identifying a set of practical and interpretable environmental criteria for evaluating a series of biorefinery strategies for a forestry company.

1.5.3 Environmental metrics evaluation for the biorefinery processes

In Life Cycle Impact assessment (LCIA), magnitude of potential environmental impacts of a product or a system is evaluated (ISO, 2006). In this step, life cycle inventory resulting from mass and energy balances are converted into environmental indicators. In impact characterization methods, impact pathway models are used to make a link between each inventory data to its potential environmental impacts (Jolliet et al., 2003). In some impact assessment methods, intermediate level of environmental impacts are evaluated (midpoint impacts), while other methods try to reach the endpoint and to describe the environmental impacts by using damage categories (ISO, 2006). IMPACT 2002^{+} evaluates the environmental impacts at both levels. Figure 1-4 illustrates midpoint and endpoint environmental impacts and their relations.

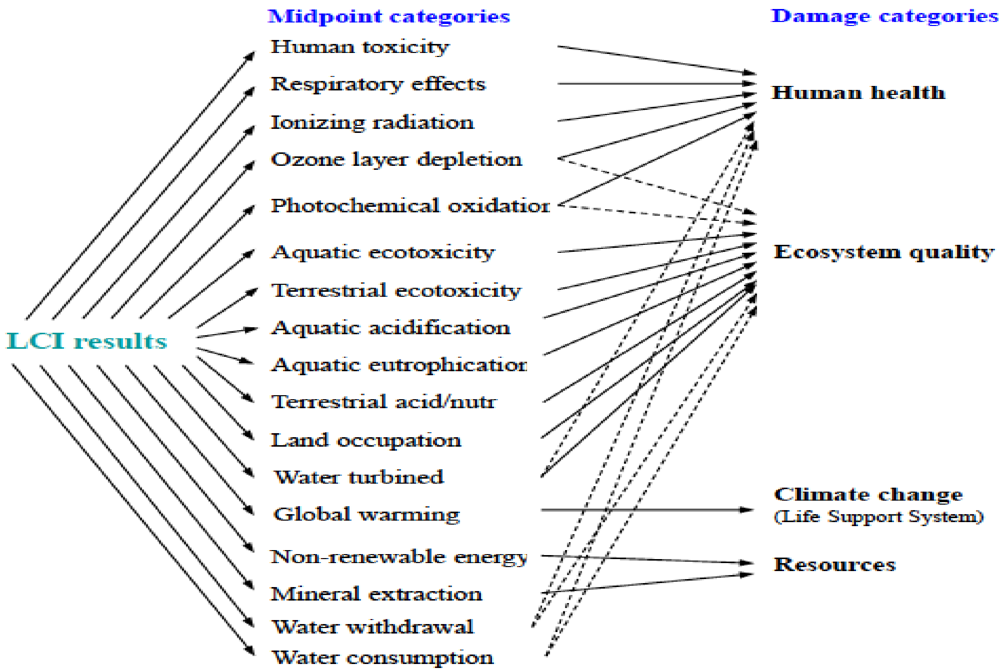

Figure 1-4 Example of IMPACT 2002+, indicators at midpoint and endpoint level (Jolliet et al., 2003)

The common environmental issues that are usually considered in the evaluation of second-generation biorefineries include greenhouse gas emissions, energy use, water use, biodiversity and landuse change (Uihlein and Schebek, 2009). GHG emissions cause interference with the climate system, resulting in global warming. Carbon dioxide, methane and nitrous oxide are the major greenhouse gases and each of them have different time horizon in terms of global warming impacts (Baumann and Tillman, 2004). Although most studies have focused on GHG and energy use that are the most often concerns for environmental aspects in biorefinery plants, new studies have paid more attention to direct Land Use Change (LUC) and Indirect Landuse Change (ILUC). It has been proved that reduction in GHG emissions, due to forest biorefinery implementation, highly depends on the inclusion of emissions from LUC and ILUC (King et al., 2010).

In the agricultural-based biorefinery and depending on the analysis methodology, the effects of landuse change on GHG balances can be positive and negative. The conversion of forests, wetlands and grasslands to cropland has a negative effect on GHG due to the emission of carbon from biomass and soils to the atmosphere. On the contrary, converting sparsely vegetated or disturbed lands to cropland results in a net gain in biomass production and sequestration of carbon into soil (King et al., 2010). Indirect landuse effects from forestry-based biorefineries should be considered as well. As an example, forest residues that are used in biorefinery processes result in feedstock shortage for the energy production. Providing energy for the industrial facilities is the main application of these residues, therefore, more wood biomass should be extracted to compensate the resources shortage and to provide energy. This results in an indirect change on the GHG balances (Gnansounou et al., 2008).

Non-renewable energy is another important environmental indicator in the evaluation of biorefinery processes. Net energy value (NEV) is the metric that illustrates the life cycle energy balance of a biorefinery project. NEV defines as the ratio of the energy produced by the system divided by the fossil energy input for the system (Malça and Freire, 2006). NEV ratios greater than unity is preferred for the biorefinery projects since it demonstrates positive life cycle energy balance meaning more energy is produced from the system than the fossil energy input.

Furthermore, water quantity that is needed for the manufacturing of bioproducts is another impediment for the project success. Pollutants, for instance fertilizers and pesticides, can adversely affect the water quality. These effects in turn result in eutrophication of fresh and ocean waters (Jacobson, 2009).

It is quite challenging to conclude that bioproducts are essentially having superior environmental performance, comparing to their equivalent fossil-based product. This is due to the scarce and limited information about some probable environmental impacts attributed to the biorefinery systems and it implies the need for profound environmental evaluations of these systems (Wellisch et al., 2010).

1.5.4 Critical analysis

If LCA methodology is properly defined and implemented, it can demonstrate the potential environmental impacts of different biomass feedstock, emerging conversion technologies and potential biorefinery products. However, despite the strength of rigorous LCA methodology, it has some limitations: requires a large amount of data, is time-consuming and expensive. In addition, the application of LCA methodology for multi-output processes with a portfolio of bioproducts is quite complex and occasionally is not well understood. It should be noted that consequential LCA is a sophisticated modelling technique and identification of the processes that are affected by changes and including them in the system boundaries is a challenging decision that may lead to dissimilar results. To alleviate such limitations, a practical LCA methodology is required that can evaluate the environmental performance of biorefinery processes with the minimum available data. Furthermore, a number of possible choices should be implemented in order to validate the robustness and sensitivity of the environmental results.

Additionally and in the context of decision-making for strategic biorefinery processes, there exist some challenges in interpreting the environmental results. Energy consumption and CO_2 emissions are well understood but still there are many difficulties regarding other environmental parameters. This is due to the complex nature and definition of some environmental metrics and it shows the requirement for more comprehensive environmental assessment methods to incorporate the whole benefits and impacts of the biorefinery implementation.

1.6 Gaps in the body of knowledge

Based on the literature review the following gaps in the body of knowledge were identified:

Phased-approach for risk mitigation

In the previous studies, the risk assessed was mainly related to process integration risks associated with the implementation of the HWE-based biorefinery. There is no study on the evaluation of HWE-based production pathways that clearly illustrates (1) market and technology risk attributed to this biorefinery process and (2) Phased approach implementation for mitigating market and technology risks associated with the HWE-based biorefinery.

Systematic approach for the sustainability evaluation of HWE-based biorefinery processes

The studies previously performed on HWE-based biorefinery processes mainly addressed the economic performance and core business related risks. There is no study in the literature defining a systematic sustainability assessment methodology for the HWE biorefinery to encompass (1) long term profitability (2) risk mitigation and (3) environmental performance.

CHAPTER 2 OVERALL METHODOLOGICAL APPROACH

In this section, first the philosophy behind the methodology is explained. Next, the case study is introduced. Finally, the methodology is presented.

2.1 Sustainability assessment: A practical methodology

As mentioned in the definition of the sustainable development, a sustainable product or service is the one that has significant economic, environmental and social performances. Particularly for the sustainability evaluation of biorefinery processes, different interpretations and various methodologies are developed. Nonetheless, few of these methods considered the risk aspect associated with the implementation of the strategic biorefinery projects. This leads to a necessity for the development of a systematic methodology to address the sustainability assessment in a practical manner, encompassing economic profitability and long-term competitiveness, environmental performance and risk mitigation approaches.

2.2 Project methodology

As explained previously, the major objective of this work is to apply a systematic and practical methodology for evaluating the sustainability of HWE-based biorefinery. Figure 2-1 illustrates the project methodology of this thesis.

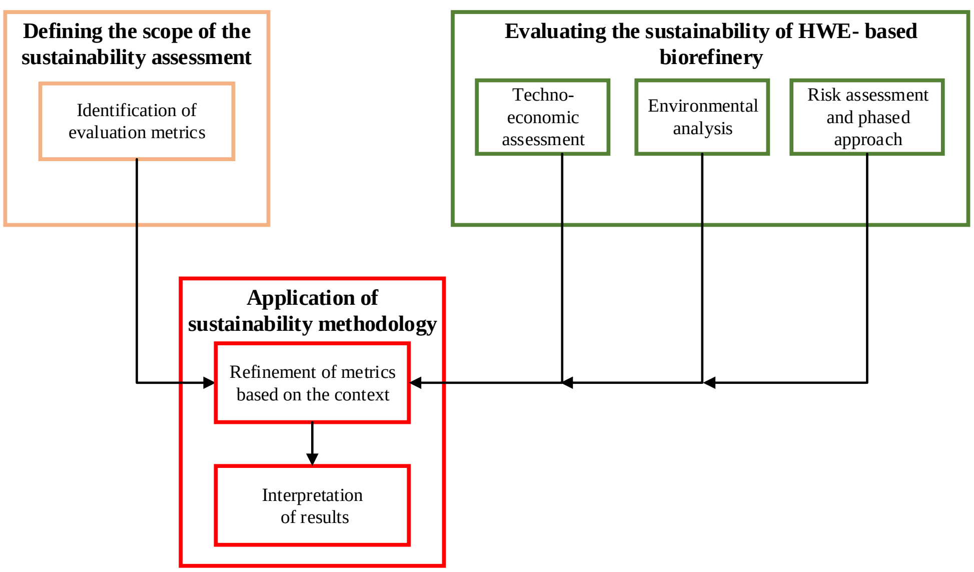

Figure 2-1 Project methodology

Before starting the evaluation steps, the scope of the sustainability assessment should be defined. This step includes the identification of the evaluation metrics that are suitable for the context of the study. Next, the identified metrics are evaluated, using system engineering tools. This part includes techno-economic assessment, environmental analysis, risk assessment and phased approach implementation. There are several metrics that are calculated in this step for instance CAPEX, OPEX, NPV, IRR, GHG, recourse consumption, etc. The last step concerns the decision-making process and applying the sustainability methodology. Considering the defined scope of the analysis and based on the context of the study, refinement of the evaluated metric are performed. A step-wise overall methodology of this thesis is illustrated in Figure 2-8.

2.3 Case study introduction

2.3.1 Mill Overview; General description

The case study mill is an integrated Canadian pulp and paper mill, producing 600 bone-dry metric tons (BDMt) per day of pulp. A simplified block flow diagram of the mill's current process is presented in Figure 2-2. In the pulp production process, 65% of the incoming feedstock is from hardwood chips, while the remaining 35% comes from recycled fiber. The pulping line produces high-yield pulp (approximately 84%) from a mixture of hardwoods.

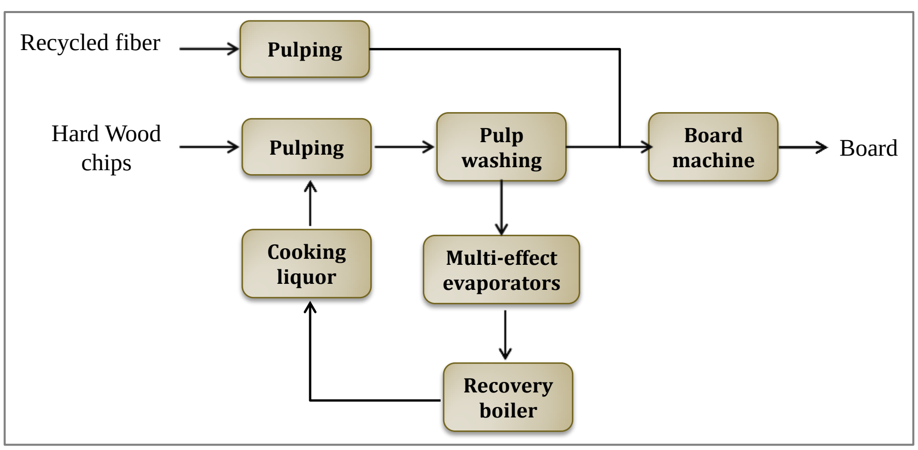

Figure 2-2 Simplified process block flow diagram of the case study mill

Energy Island at the existing mill consists of two types of boilers for the steam production, which use biomass and oil as fuel sources (80% of the steam is provided by bark boilers and 20% by oil boilers). All the electricity used in the mill is purchased from the local power grid. The mill consists of the following major process sections:

- Virgin and recycled fiber production
- Black liquor evaporation
- Clean water production
- Steam production
- Waste water treatment

The mill intends to transform its business model. The objective over the long-term includes diversifying the product portfolio by implementing a full-scale HWE-based biorefinery, as well as transforming the extracted hemicellulose into a variety of value-added products, which will improve profitability.

2.3.2 Potential integrated biorefinery process options

In the biorefinery projects, two major types of bioproducts can be manufactured: large-scale commodity products, and low-volume/high-value fine (specialty) products (Fernando et al., 2006). The commodity chemicals are mainly limited to biofuels, e.g. ethanol, butanol, diesel, low-grade sugars, etc. There is usually a huge market with strong competition for the commodity products and biofuels, especially in countries like United States and Brazil. Specialty and fine chemicals are believed to be the promising production pathways for the biorefinery processes since they present higher profitability compared to traditional pulp and paper products and the market competition for these products is less than that of the commodity products.

Regarding the forest biorefinery projects, it is recommended to have diversified product portfolios. Meaning that, it is imperative to have the co-production of commodity products along with low-volume but high-value products. Due to the sever market conditions like seasonal demand and market downturns, product diversity leads to risk mitigation. On the other hand, this coproduction enables biorefineries to maximize the value generated from the forestry feedstock.

In this work, HWE pretreatment considered to be integrated at the mill to extract hemicellulose from wood chips prior to the pulping process. Based on characteristics of the mill and HWE technology, five biorefinery process options are selected for this analysis. It is worth mentioning that the design of HWE-based biorefinery options in this study was inspired by the biorefinery processes that were developed by American Process Inc. (Restina and Pylkkanen, 2013 and 2014) (Pylkkanen, 2014). Integration of biorefinery in the mill processes in terms of mass and energy, along with a co-location at the existing mill site are considered for each following HWE-based production pathway:

A) Extraction of a dilute hemicellulose stream for anaerobic treatment and biogas production

B) Extraction and concentration of hemicellulose (70% dry solid) for animal feed and acetate salt

C) Extraction and concentration of hemicellulose stream (50% dry solid) for C5- sugars and acetate salt

D) Production of C5-sugars and acetate salt

E) Production of furfural and acetate salt

Figure 2-3 presents a simplified block diagram, including the major process unit operations for the existing P&P process and the five-biorefinery options. For all options studied, capacity of the existing pulp production line at the mill is kept constant and the hemicellulose pre-extraction process is added to the fiber line.

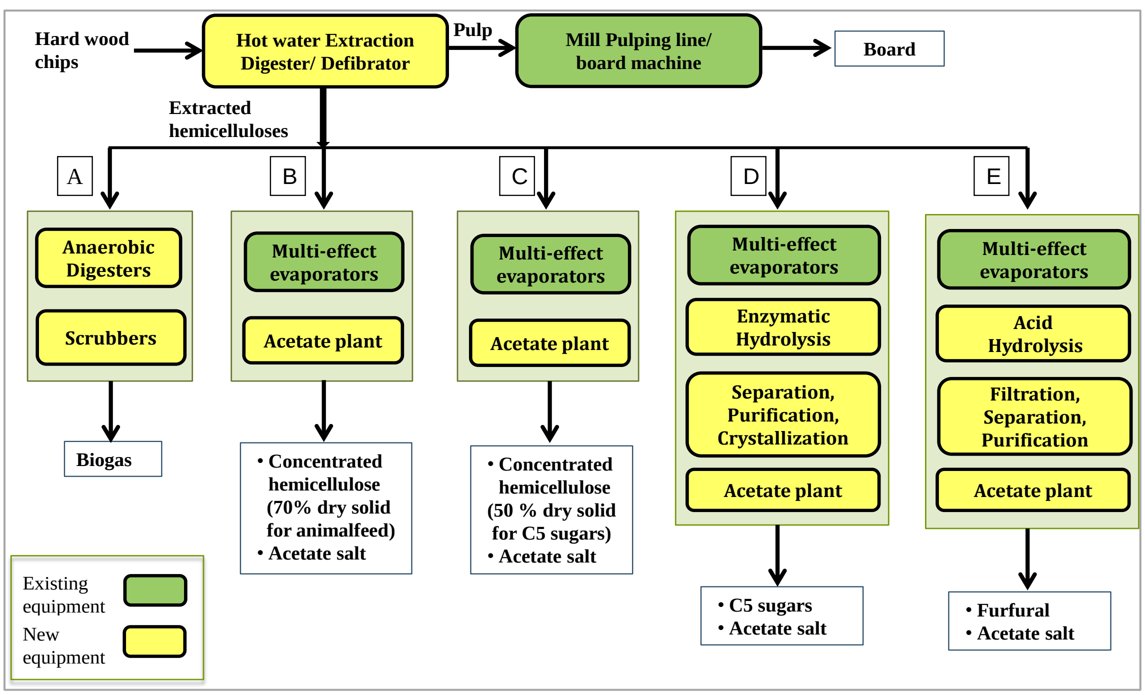

Figure 2-3 Simplified process block diagram of HWE-based production pathways

Following the analysis of the available resources at the mill, the feedstock to the biorefinery is defined to be the mixed hardwoods (maple, birch, and aspen) and hemicellulose extraction is carried out in a HWE digester vessel. Afterwards, the pre-treated pulp passes through the continuous pulp production line. As previously mentioned, pulp yield and quality are dependent on the degree of hemicellulose extraction. For maintaining the pulp quality, a relatively low extraction rate (approximately 10% mass removal) is considered and it is assumed that this rate of extraction will not affect the pulp quality. This extraction rate is used as a basis for mass and energy balances in the assessment of the biorefinery products.

2.3.2.1 Anaerobic treatment; Biogas

In process option A; anaerobic treatment is performed on the dilute hemicellulose stream. Anaerobic digestion is a series of processes in which microorganisms break down and digest the biodegradable components. This process is conducted in the absence of oxygen. The treatment system is designed to remove the organic pollutants that contribute to biological and chemical oxygen demand (BOD and COD respectively) content of the effluent stream. The digestion process starts with bacterial hydrolysis of inlet material. Insoluble carbohydrates are broken down to soluble derivatives, ready for the microorganisms. Bacteria convert the sugars and amino acids into carbon dioxide and methane (as the main components of biogas). The biogas generated in the anaerobic digester is removed using biogas blowers and sent to a biogas scrubber for H_2S removal. Then, the scrubbed biogas is compressed by biogas blowers and is sent to the steam boilers.

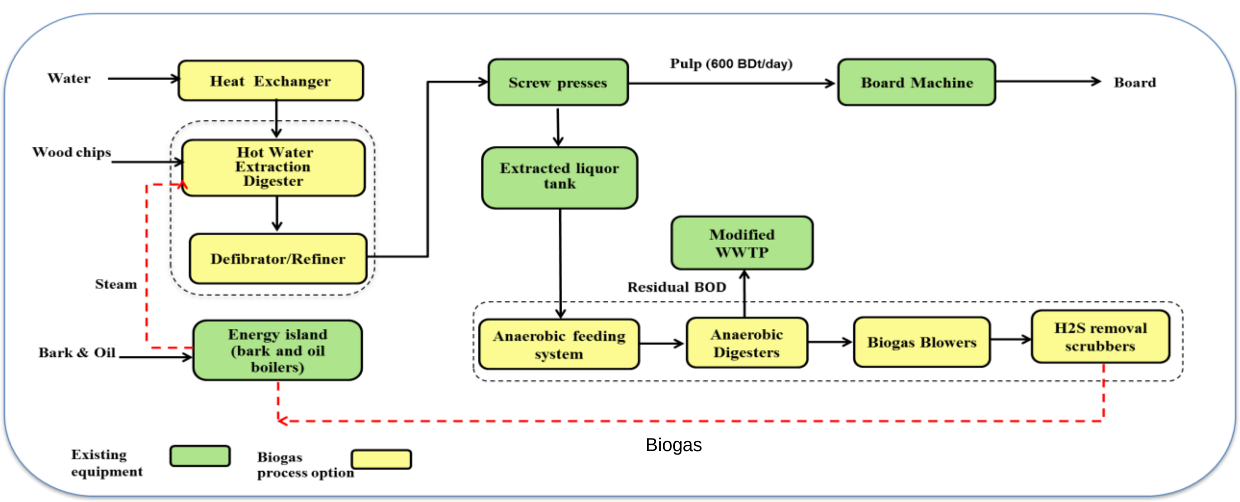

Figure 2-4 Biogas biorefinery option

Figure 2-4 shows the main steps in the biogas production process. In this option, the existing evaporators at the mill are retired and biogas produced is assumed to replace a portion of bark that is currently used for steam production at the case study mill.

2.3.2.2 Concentrated hemicellulose for animal feed and C5-sugars

An emerging market for hemicellulose is a feedstock to supply producers of bio-fuels, sugars, furfural or other different types of products. The output stream quality (concentration of hemicelluloses, composition and sugar content) must meet the requirements according to the intended application. In process options B and C, the extracted stream is concentrated by a series of re-allocated multi-effect evaporators to different concentration levels. In option B, the sale of concentrated hemicellulose for animal feed application is considered. The molasses product should have at least a 70% sugar concentration in order to meet appropriate calorific content. As for process option C, the extracted stream is concentrated to 50% to be sold to C5-sugar producers. In both options B and C, permeate from the evaporation contains a considerable amount of acetic acid which is recovered by filtration. Further concentration of acetate salt is performed via existing multi-effect evaporators (Figure 2-5).

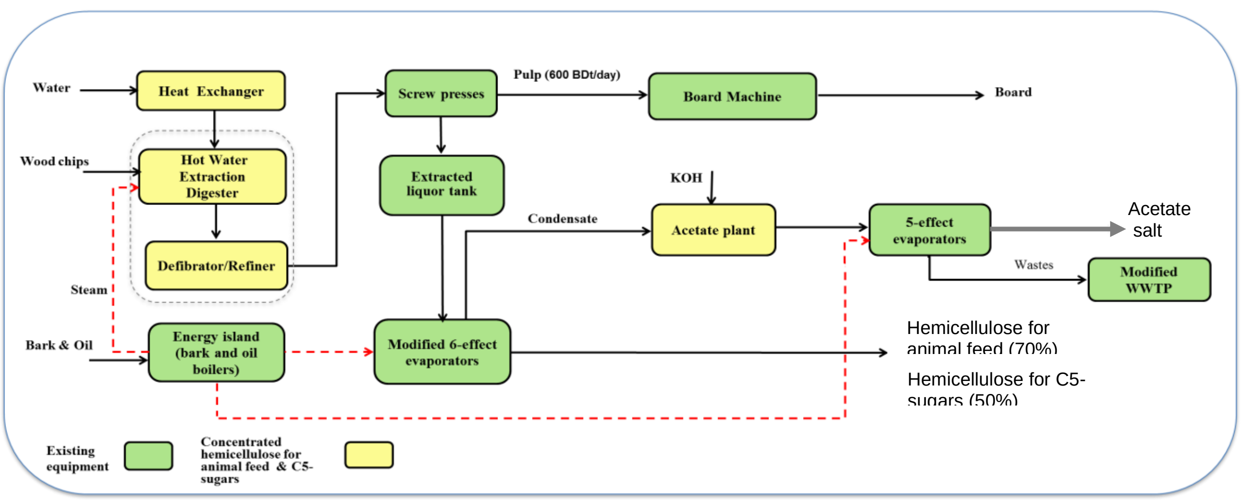

Figure 2-5 Concentrated hemicellulose for animal feed and C5-sugars biorefinery processes

Acetic acid is used as feedstock to produce different acetate salts like sodium acetate, aluminum acetate, ammonium acetate, potassium acetate and calcium-magnesium acetate. In this study, acetate salt is planned to mainly use as de-icing agent due to its lower aggressive and corrosive characteristics, compared with existing de-icing substances (Deicing2014).

2.3.2.3 Enzymatic hydrolysis; C5-sugars and acetate salt

In process option D and following the pre-treatment and evaporation stages, the concentrated hemicellulose is sent through enzymatic hydrolysis and sugar purification steps. This process yields C5-sugars as the main product (with low levels of contamination) and acetic acid as the co-product. Not only acetic acid is recovered from the evaporator's permeate stream, but also some acids are produced during the enzymatic hydrolysis stage. Figure 2-6 illustrates the main process steps in the C5-sugars and acetate salt production pathway. C5-sugars are natural sugars that can be found in some woody materials such as straw, pecan shells, cottonseed hulls, and corncobs. It is a great alternative to white sugar and has none of the negative side effects of sugar. The majority of C5-sugars are used to produce xylitol, which is a bulk sweetener with recognized unique dental benefits. Other applications of C5-sugars are as an additive in pet food, anti-oxidants for foods as well as pharmaceutical uses (Schoenhals, 2003). The dominant producers of C5-sugars are developing countries of east and Southeast Asia. Details regarding the market status of C5-sugares are explained in section 3.3.1.

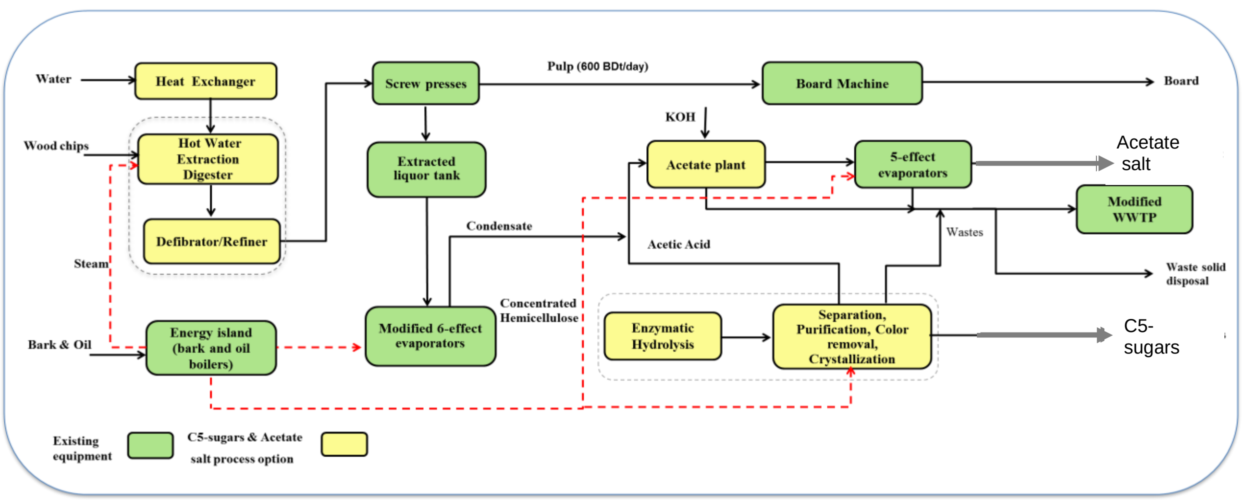

Figure 2-6 C5-sugars and acetate salt biorefinery option

2.3.2.4 Acid hydrolysis; Furfural and acetate salt

Production of furfural and acetate salt is performed in process option E. The pre-extracted hemicellulose stream is concentrated in the multi-effect evaporators and then it is hydrolyzed by aqueous sulphuric acid in the presence of heat. This process yields pentose sugars, mainly xylose. Under the same conditions of heat and acidity, xylose is dehydrated to furfural. The product purification step is performed by using liquid-liquid extraction. Figure 2-7 shows the main process steps in the furfural production process. Furfural is a chemical that can be used for several applications including recovery of lubricants from cracked crude, feedstock for the production of furan resins, also called furfuryl alcohol resins and flavour compound (Win, 2005).

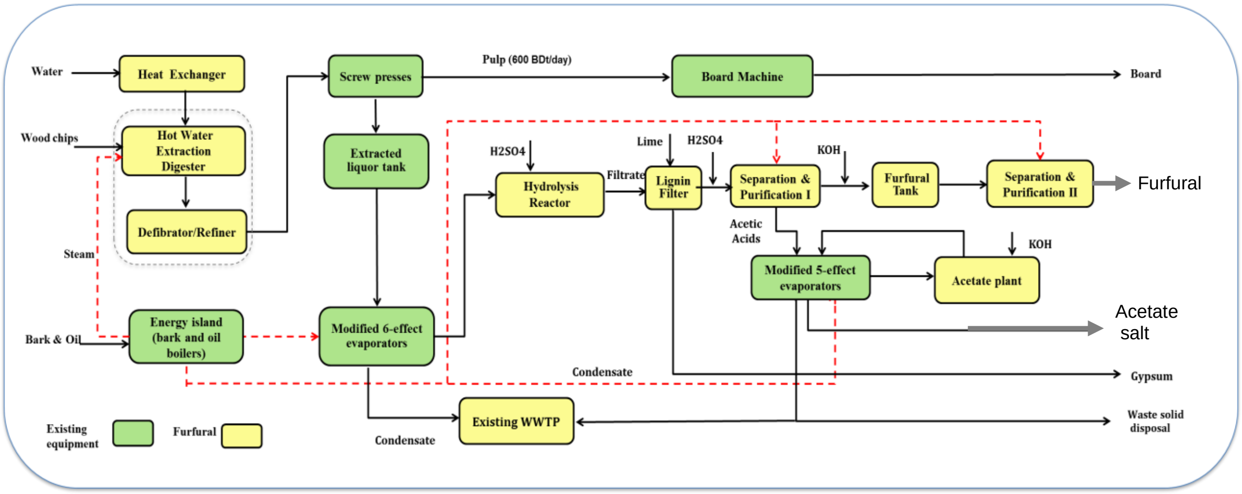

Figure 2-7 Furfural and acetate salt biorefinery option

Furfural has the unique property to dissolve aromatics and other unsaturated olefins. It has several applications including: Solvent for refining the lubricating oils & decolorizing agent, reactive solvent and wetting agent and feedstock for other furan derivatives. Furfural is currently produced in Dominican Republic and China and is delivered to North American or European markets. Global market estimated to exceed 250,000 tons/year and to be growing further (350,000 tons/year in 2020). Details on the market status of furfural are explained in section 3.3.1

2.4 Overall methodology

The implemented methodology for this project starts with the identification of potential HWE-based process-product alternatives, and continues up to the implementation of different scenarios including the phased approach and performing a techno-economic evaluation, environmental assessment and simplified risk analysis with regard to the defined process options. Figure 2-8 shows the stepwise methodology of this master project. Modelling of HWE-based biorefinery options is performed based on very detailed and accurate information reflecting relatively true production conditions. Using the primary data from literature review and the technology providers, process block diagrams are developed for each biorefinery process option and mass and energy balances are performed, based on a "large block analysis" (Janssen et al., 2006) approach with the combined use of apiMAX™ simulation software and Microsoft Excel. Large-block analysis is used as a design basis, presenting the potential process systems by a series of large blocks, which are characterized by mass, and energy balances (inputs, models and outputs).

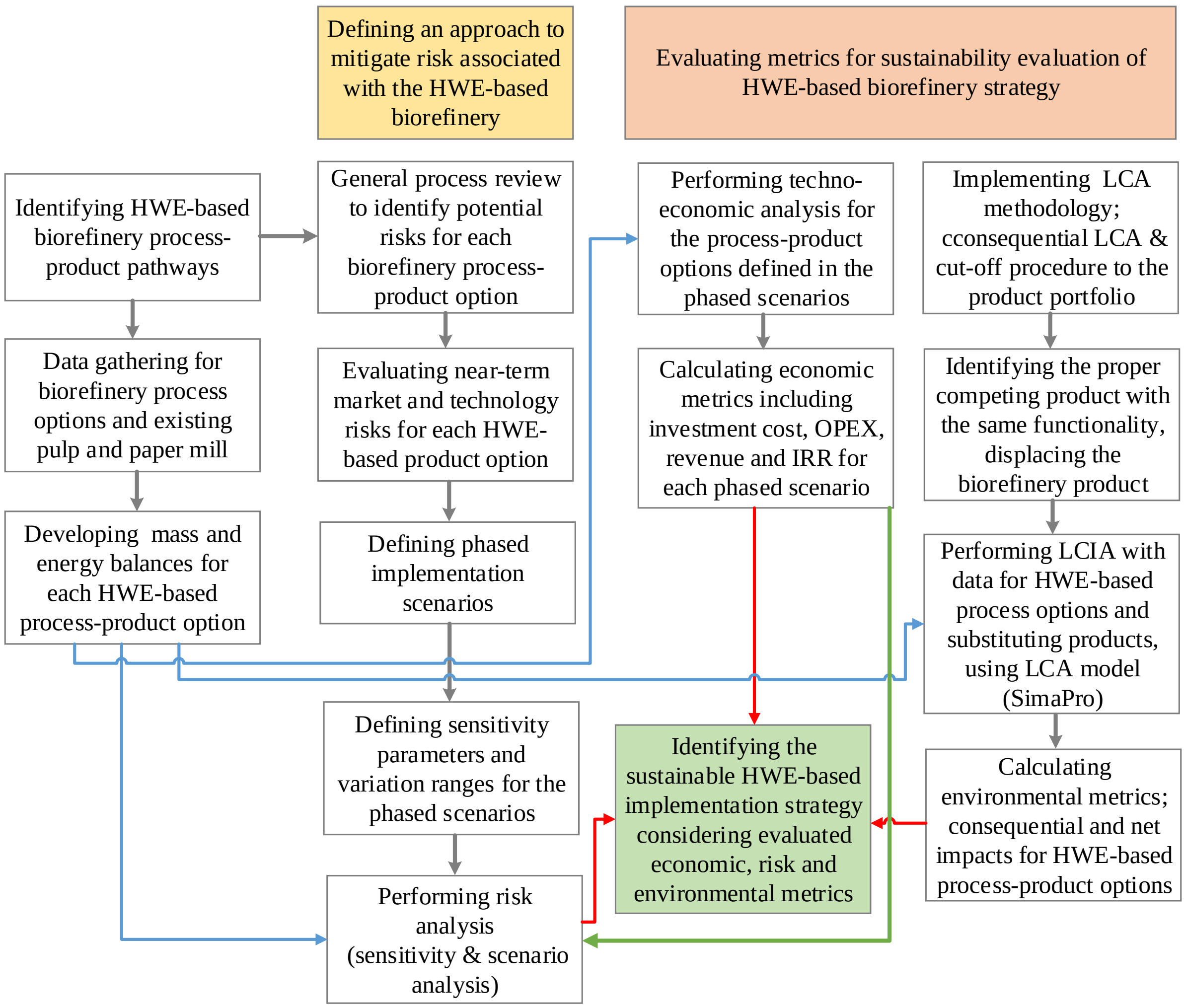

Figure 2-8 Overall project methodology

A systematic techno-economic analysis is carried out in order to calculate the capital costs, cash flow and the profitability of the process options for different scenarios. Considering the risk analysis, a qualitative evaluation of the near-term market and technology risks associated with each production pathway is performed and three investment phases are defined. As the next steps in the risk analysis, sensitivity analyses for the options in the second scenario, also for all the defined process options are conducted.

Sensitive parameters that may have an impact on the profitability are defined following a market review also considering the study context and the identified market and technology risks. In the context of the sensitivity analysis, three parameters are selected: capital cost (CAPEX), operating cost (OPEX) and revenue. It is worth mentioning that a sensitivity analysis is performed to examine the impact on project profitability based on variations of external factors and high-risk parameters to highlight the impacts of each individual sensitive parameter. Furthermore, sensitivity analysis is conducted for each process option defined in the scenarios, assuming that all the identified sensitive parameters are occurring at a single time (simultaneously for the worst-case scenario).

Concerning the environmental analysis, the LCA methodology includes data collection for the biorefinery process options and the existing mill, along with the definition of goal and scope, functional unit and system boundaries. Following the methodology of consequential LCA, environmental impacts through the life cycle is assessed using a “cradle-to-gate” perspective for five production pathways, which are defined for the valorization of the extracted hemicellulose stream. In particular, consequential LCA methodology is employed to evaluate the potential environmental consequences and incremental impacts of the integrated biorefinery process options. Four end-point impact categories are calculated: climate change, human health, ecosystem quality and resources. Consequential and net results are used to highlight the motivation for replacing the fossil- and agricultural-based products by bioproducts.

Detailed descriptions of the methodological steps performed in this project are presented in the following section.

2.4.1 Risk analysis and phase approach implementation

2.4.1.1 Risk analysis

Risk analysis in process design follows four main steps, identification of sources of uncertainty, quantification of uncertainties, formulation of uncertainty for risk analysis, and quantification of risk. Risk analysis in the context of this study mainly covers two types of potential risks; market and technology risks for each product stream. Technology risks also include risks that might impact the mill’s core business.

2.4.1.2 Technology risk

Details on the technology risks that should be taken into consideration prior to investment on a biorefinery project are explained in section 1.3.1.2. Technology risks considered in this project covers the following topics:

- Process complexity
- Scale-up complexity (function of the number of units)
- Current existing scale versus targeted scale
- Access to technology

Investors and technology providers, who are intended to integrate a biorefinery technology for the first time at the commercial scale, should expect a high level of technology risks and uncertainties; Since there are no commercial experiences or available guidelines regarding the emerging biorefinery technologies in the literature. Process integration risks mainly include the limitations in the material handling systems, steam and power generation and waste treatment. Higher steam and power demand for the biorefinery process brings the existing operation close to the limits and increase the process risks. Likewise, the greater the amount of the waste generated from the biorefinery, the higher pressure and risk will be on the waste treatment systems.

Concerning the risks to the core business as previously stated, integrating a HWE-based biorefinery into a mill may contribute to sever adverse effects on the pulp quality and pulp mechanical properties. Based on a series of lab tests that were conducted on the pulp from HWE digester, it is proved that there is a potential risk of losing pulp quality and deteriorating the pulp mechanical strength at high hemicellulose extraction rates.

2.4.1.3 Market risk

Details on the market risks are explained in section 1.3.1.3. Market risks considered in this project covers the following topics:

- Market size (local, regional and global)
- Market growth
- Market Competition

- Product transportation
- Feedstock availability and price
- Downstream development opportunities

Market size essentially influences a plant in identifying downstream markets. Large market facilitates the selling of product but implies strong competitions. On the contrary small and undeveloped market leads to difficulties to find stable downstream industries. However, it represents a greater opportunity for the product to penetrate the market and establish itself for future. Market growth is an indicator of stability and reliability.

Near-term market and technology risk assessment for the HWE-based biorefinery production pathways are illustrated in Table 3-1. This preliminary market and technology risk analysis leads to the definition of the phased-scenarios that are explained in the following section.

2.4.1.4 Definition of phased-scenarios

Phased scenarios are developed considering the case study mill, available feedstock, potential markets for the products and the risks described in the previous section. Three scenarios are defined using the five above-mentioned biorefinery process options, to be implemented in two investment phases. (Table 2-1)

Table 2-1 Phased implementation scenarios

Scenario	**Scenario implementation** → **Time**	**Process option**
Commodity products	→ Phase I → ╣	1. Biogas 2. Concentrated hemicellulose for Animal feed & Acetate salt
Commodity products to added-value products	→ Phase I → Phase II	1. Hemicellulose for C5- sugars & Acetate salt 2. C5- sugars & Acetate salt (Incremental) 3. Hemicellulose for C5- sugars & Acetate salt in phase I and C5- sugars & Acetate salt in phase II
Added-value products	→ Phase II → ╣	1. C5-sugars & Acetate salt 2. Furfural & Acetate salt

The first scenario uses process option A or B in the first investment phase of the project. The third option of the second scenario combines process options C and D into a two-phased investment strategy, where process option C will be implemented in phase I (the first 5 years of production) and subsequently process option D in phase II. Additionally, acetate salt is considered as a co-product in both stages of production. The third scenario refers to the hemicellulose pre-extraction and directly processing the extracted stream for producing the added-value products (C5-sugars or furfural). Knowing that the technology and market risks associated with these products are medium, they are considered to produce in phase II of the project. It is important to highlight that the production of these products (i.e. C5-sugars and furfural) is considered to start immediately after biorefinery implementation and hemicellulose extraction (in the first investment phase of the project). The term “Phase II” does not imply the time interval but it represents the added-value products in the third scenario.

Table 2-2 summarizes the characteristics of the defined scenarios. Generally, the first phase of each biorefinery strategy represents a low-risk, short-term process arrangement in which a commodity product is manufactured. The objective of this phase is risk mitigation and short-term viability. Whereas phase II involves technology that when implemented, typically results in manufacturing of added-value products and causes higher revenue. However, this phase associates with greater market and technology risks and partnerships are essential to minimize the risks.

Table 2-2 Characteristics of the phased scenarios

Scenario	Targeted attributes to keep option for further analysis
1	Large volume / limited margins / Lower market & technology risks / subsidies are possible in near term
2	Stage wise development/ lower market & technology risks/ small but growing product demand for phase II product/ Partnership (Joint Venture) is recommended for phase II
3	Early to market/ higher market and technology risks/ market for phased II product must be available in the near term/ Partnership (Joint Venture) is recommended

2.4.1.5 Sensitivity analysis

A proper risk analysis method should be selected depending on the goal of the study. The sources of uncertainty and information availability are other factors that influence the analysis approach. In this study, a qualitative risk assessment is performed to evaluate the level of market and technology risks associated with the HWE-based biorefinery products. Four qualitative levels are defined in this step to illustrate the importance of the identified uncertainties. Table 3-1 shows the near-term risk assessment results for the HWE-based biorefinery product options and their justifications.

In the next step, a sensitivity analysis is carried out for the options in the second scenario, to examine the impact on project profitability due to variations in already identified sensitive parameters (Table 3-2). In this analysis, same probability value is considered for all the parameters and analysis is performed using the boundary values. Sensitive parameters are considered one at a time, meaning that other parameters remained constant at their expected values (base case values) while analyzing the sensitivity of the economic performance to the parameter that is varied. Sensitive parameters in this project include CAPEX, OPEX and revenue. In addition for the C5-sugars, process yield is considered as an uncertain parameter. Variation ranges (minimum and maximum values) are used for these parameters and the internal rate of return is employed as the economic metric for the sensitivity analysis. The objective of this step is to identify the uncertain parameters that have the substantial impact on the economic profitability.

In the last step of the risk analysis, another sensitivity analysis is conducted. As explained before, this step is mainly intended to demonstrate the concept of risk mitigation and strategic planning. A series of sensitive parameters (called as scenarios) is utilized to conduct the analysis. The scenarios are defined following the near-term market and technology risk assessment and identified sensitive parameters for all the HWE-based process options. Due to the lack of concrete information regarding the likelihood or probability of the defined sensitive parameters, an ordinal scale is used for the quantification of the sensitive parameters. For each level of market and technology risks, a conversion factor is subjectively defined. Table 2-3 illustrates the defined conversion factors for the analysis.

Similar to the previous sensitivity analysis, variation ranges of sensitive parameters are employed (Table 3-2) along with conversion factors and the internal rate of return is used as economic metric. Table 3-3 shows the sensitive parameters that are selected for the analysis of the biorefinery options. The objective of this step is to incorporate the sensitivity analysis results in the sustainability evaluation of HWE-based biorefinery and particularly to benchmark the single-phased and two-phased scenarios.

Table 2-3 Conversion factors for qualitative risk scores

Risk level	Conversion factor
None	0%
Low	20%
Low-medium	40%
Medium	60%
Medium-high	80%
High	100%

2.4.2 Techno-economic analysis

The economic analysis in this work is performed following standard methods, as described by Peters and Timmerhaus (Timmerhaus and Peters, 2004).

2.4.2.1 CAPEX estimation

The total capital investment costs are developed for direct and indirect costs. For equipment costs, the first step is to use equipment lists presented in the NREL reports, related to the more mature technologies (Kazi et al., 2010) (Humbird et al., 2011), and filter out only the equipment that is similar to those defined in this study. Moreover, the references for capital cost estimates are obtained from vendor quotations for some of the equipment. In order to adjust the equipment size, a scale factor between 0.5 and 0.7 is selected. Subsequently, the equipment costs are indexed with respect to their quotation year. The considered cost indexes for the present study are the chemical engineering equipment cost indexes. Then, the costs are multiplied by an installation factor (range between 1.3 and 2.5). The resulting cost, which is called the total installed cost, actually takes into account the great majority of direct costs. Piping, civil works, electrical and instrumentation costs are also calculated based on a certain percentage of the total installed equipment costs. The costs of these activities plus the total installed equipment costs lead to the total direct costs. It is assumed that the case study mill has sufficient waste treatment capacity and only minor modifications are required to accommodate the effluent streams from the new processes. Working capital is also calculated following these assumptions:

- 15 days of feedstock supplies
- 20 days of product storage
- 30 days of raw materials and chemicals inventory

Total indirect costs are related to basic and detailed engineering works. Project management, basic engineering and detailed engineering costs are multipliers of 0.04, 0.08 and 0.12 of total installed equipment. The total investment cost is the sum of total direct cost, indirect costs and the working capital.

2.4.2.2 OPEX estimation

The variable costs include expenses related to the feedstock, consumables and chemicals. Table 2-4 presents the values, which are considered for the feedstock and utilities, consumed in this project. These values defined following the information received from the mill also the data that are available in the literature. The operation of the mill and HWE-based biorefinery options is 345 working days in a year.

Table 2-4 Variable production cost; feedstock, chemicals and utility prices

Variable production Cost	Units	$/unit
Biomass , Dry	BDt	50
H2SO4	t	205
Lime	t	224
Gypsum and lignin from filter (50%)	t	2
Electricity Consumed	MWh	46
NaOH at 50% strength	t	345
Avoided chemical cost	Units	-
KOH as 50% strength	t	842
WWTP Polymer solution as 50% strength	t	308
Aluminum sulphate as 49% solution	t	517
Hydrogen Peroxide as 37% solution	t	816
Waste Solids disposal	BDt	2

Regarding the other parameters in the production cost following basis are applied:

- Based on an energy and steam analysis, it is planned that 100% of the total produced biogas is used in the existing bark boilers. This contributes to partial reduction in the bark consumption of the boilers.

- Pulp yield is assumed to increase from currently 83.5% to future 90%, leading to 50 BDt/day of woodchips savings.
- It is assumed that the labor cost will remain the same, i.e. labor savings from shutting down some parts of the mill (following the biorefinery implementation) will be compensated by additional labor needed to operate the biorefinery.
- Accelerated 5 year deprecation rule has been used.
- Annual maintenance is assumed to be 1% of total installed capital cost.
- Marketing and supplies are assumed to be 2% of annual revenue.
- Property taxes and insurance are assumed to be 0.25% of total installed capital cost.

2.4.2.3 Products selling price

The product-selling price is set according to the market survey and information extracted from the literature. It is worth mentioning that product price for each HWE-based production pathway includes the cost related to the transportation of bioproducts from the mill to the potential customer. The annual revenue breakdown for the defined HWE-based process options is presented in Figure 3-4.

2.4.3 Life cycle assessment methodology

Life cycle assessment is used as an analytical tool and environmental analysis is performed following the standard practices that are defined by the ISO 14040 series (ISO, 2000b, ISO, 1998, ISO, 2000a, ISO, 2006). In addition, modelling of processes and impact assessment are carried out using SimaPro 8.0 Multiuser LCA software and IMPACT 2002$^+$ (version 2.15), respectively (Goedkoop et al., 2008). Regarding the Life Cycle Inventory (LCI) database, Ecoinvent AmN CIRAIG is employed. This database is developed by Interuniversity Research Centre for the Life Cycle of Products, Processes and Services (CIRAIG), to adapt the international ecoinvent database to the Quebec and Canadian contexts.

As illustrated in Figure 2-9, main steps in the life cycle of a biorefinery process consists of: Raw material acquisition and extraction from natural resource including biomass harvesting and preparation, bioproducts production through biorefinery processes including biochemical and thermochemical pathways, product transportation and distribution and ultimately product recycling, reuse or final disposal.

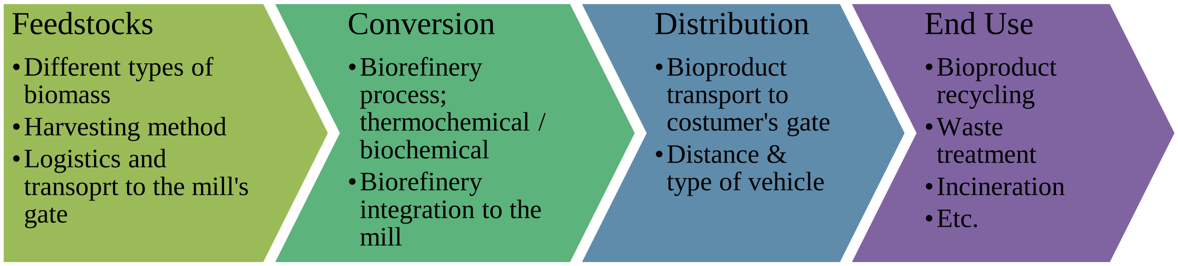

Figure 2-9 Main steps in the lifecycle of an integrated biorefinery process

2.4.3.1 Goal and scope

The goal of this LCA study is to analyze the environmental performance of different HWE-based biorefinery process options on a transparent and comprehensive basis in order to compare; (A) the environmental results of different HWE-based biorefinery options, using the consequential impact perspective, and (B) to analyze the net environmental benefits relative to the impacts from the board production in order to provide a perspective on the importance of changes in the environmental performance due to the implementation of different HWE-based biorefinery production pathways. The scope of this study is Cradle to Gate; potential environmental impacts are evaluated from the feedstock growing and harvesting until delivery of bioproducts to the gate. Gate is considered as the targeted customer's gate for the defined biorefinery options.

2.4.3.2 Consequential LCA and cut-off procedure

The implemented approach for defining the system boundaries in this work is the consequential LCA perspective along with the system boundary expansion and cut-off procedure (Figure 2-10). To perform the cut-off procedure for eliminating the similar processes from the system boundary, the mill is required to produce the same amount of pulp and final product (before and after biorefinery implementation). If the mill does not implement the biorefinery process and continues to produce the existing board, the environmental impacts will remain the same as before.

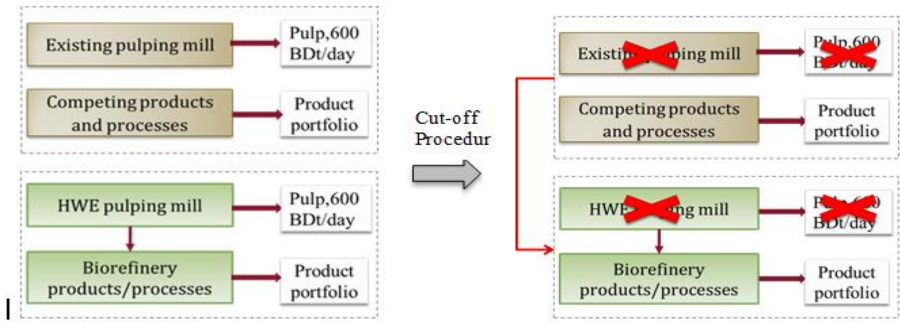

Figure 2-10 Basis for consequential LCA and cut-off procedure

2.4.3.3 Functional unit

LCA is often performed using a functional unit that refers to the output or product of a process or system. However, HWE-based biorefinery options under investigation have different production capacities. Therefore, functional unit in this analysis is considered as the portfolio of products that are generated by different biorefinery options and at the same rate of hemicellulose extraction. In other words, life cycle inventory and life cycle impacts are calculated for a reference flow of approximately 310,000 ton per year of dilute hemicellulose stream with 5% solid that is used for different production pathways. By considering this functional unit and ensuring the rigorous application of consequential analysis in each case, the process options are made functionally equivalent. Due to the cut-off procedure, the existing pulp and paper mill product is not considered in the functional unit. The operation of the mill and HWE-based biorefinery options is 345 days in a year.

2.4.3.4 System boundaries definition

Competing products are the competitors of biorefinery products on the existing market. Consequently and based on the calculation methodology, by transferring all the avoided impacts from the competing products and processes, the environmental benefits and negative impacts are allocated and credited to the new biorefinery strategies and bioproduct portfolios. Subsequently, the system boundary includes the HWE-based biorefinery processes and their input material and emissions, also the fossil- or agricultural-based products that can be partially displaced or substituted by the bioproducts. Moreover, minor changes that will be applied on the pulping process while implementing the HWE-based biorefinery are considered in the system boundary.

Figure 2-11 illustrates the system boundary for C5-sugars and acetate salt production; the cut-off parts are shown in brown color.

It should be noted that nearly similar system boundaries are developed for all the defined HWE-based production pathways. The major differences between the alternatives concern the use of chemicals and other consumables, environmental emissions and most importantly their differences regarding the individual processes and key operating process units.

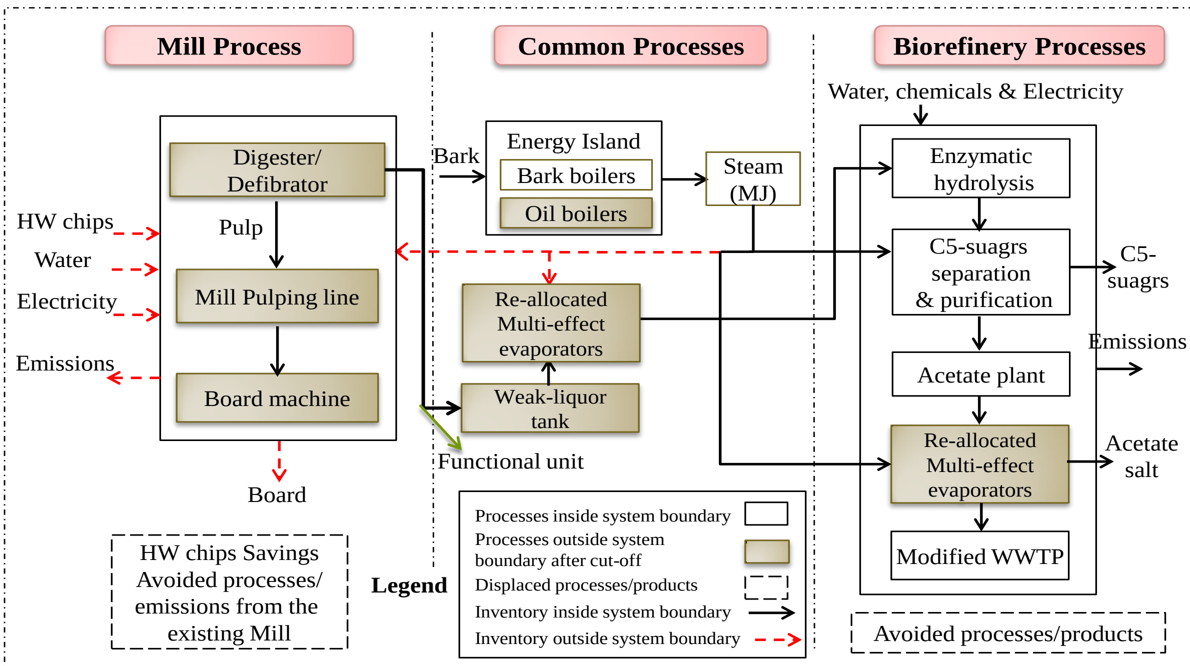

Figure 2-11 System boundary for C5-sugars and acetate salt process option

2.4.3.5 Data sources

Sources of data for the life cycle inventory include mass and energy balances of the existing mill, publically available data from the literature review and data from technology providers. In addition, North American data that is available in SimaPro software is applied in cases of primary data limitation and scarcity of information, particularly for chemicals that are used in the HWE-based biorefinery process and for bioproducts substitutes. For the steps regarding the procurement of forestry feedstock, bark, chemicals, electricity and other required input material to the mill, available data from mill is used. Data quality can be considered nearly high since they are mostly uniform and updated. Regarding the substitute products, available proxies from SimaPro are used.

2.4.3.6 Environmental impacts assessment

In this assessment, four endpoint impact categories including climate change, human health, ecosystem quality, and resources are considered. Generally, midpoint impact categories are mostly preferred for hotspot analysis; nonetheless, in this study endpoint impact categories are presumed to be an adequate basis to illustrate the overall environmental performance of different HWE-based biorefinery alternatives for strategic decision-making purposes.

2.4.3.7 LCA parameters

Following the objectives defined for this LCA analysis, calculations are performed in several steps. Table 2-5 presents the definition of environmental parameters that are evaluated. Consequential LCA results are assessed to show the potential environmental impacts on the implementation of HWE-based biorefinery process. Overall LCA parameters are related to the impacts of biorefinery processes, and to those of the avoided products and processes. Net results are evaluated by summing up the contributions of all inventory compartments within a defined impact category. Thereafter, net results are normalized to analyze the environmental benefits of integrating a HWE-based process into the case study mill. Ultimately, reduction of GHG emissions is calculated for each biorefinery option based on the ratio between the net climate change impacts and the avoided ones.

Table 2-5 Definition of LCA environmental parameters

Results	Interpretation	Definition
Consequential	Incremental impacts of biorefinery implementation, positive contribution to environmental impacts	
Overall	Incorporating the impacts of avoided processes and products, and the biorefinery impacts	
Net	Sum of the positive and negative impacts of all inventory parameters	$\sum_{i=1}^{5} \text{overall impacts}$
Net normalized	Net results relative to the cut-off case	$\text{Ni} = \frac{\text{Net environmental impact, i}}{\text{Environmental imact of existing mill}}$
GHG reduction	Net climate change results relative to the avoided impacts	$\text{GHGi} = \frac{\text{Net climate change impacts, i}}{\text{Displaced climate change impacts, i}}$

CHAPTER 3 PUBLICATION SUMMARY AND SYNTHESIS

3.1 Presentation of publications

Following articles that are submitted to peer-reviewed scientific journals can be found in Appendices A to B of this thesis.

- Gilani, B. &Stuart, R. P. (2014). Mitigating risk through phased biorefinery implementation. *Submitted to Bioresource technology*
- Gilani, B. & Stuart, R. P. (2014). Life cycle assessment of an integrated forest biorefinery: Hot water extraction process case study. *Submitted to Biofuels, bioproducts and biorefining journal (Biofpr)*

3.2 Links between publications

In the first paper, phased approach for mitigating the technology and market risks associated with a HWE-based biorefinery process proposed. This paper summarized the techno-economic potentials of the HWE-based production pathways and evaluated the market and technology risks associated with these options. Ultimately, the best option considering the return and the risk mitigation was identified (Appendix A).

In the second paper (Appendix B), a practical LCA methodology was applied to evaluate the potential environmental impacts associated with the implementation of HWE-based biorefinery process. Then, using the techno-economic and risk analysis results from the first paper and coupling them with the evaluated environmental results, sustainability assessment of HWE-based biorefinery options was carried out.

The summary of the publications are presented in Figure 3-1.

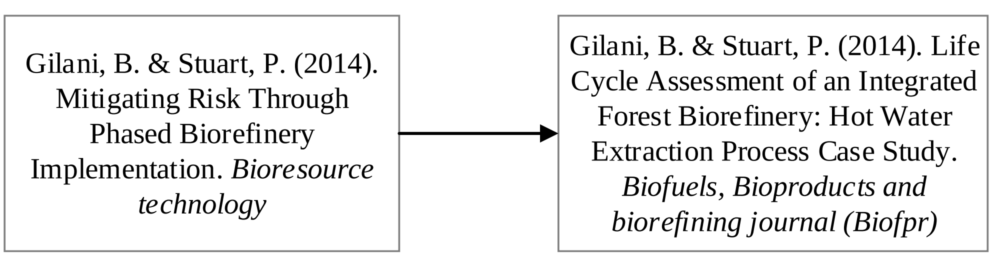

Figure 3-1 Publication summary

3.3 Synthesis

This synthesis presents the main results of the work performed in this Master project in order to address the implemented methodology. The focus is on four critical aspects: 1) Risk analysis and the importance of implementing a phased approach to mitigate technology and market risks 2) Evaluation of the metrics related to the economic performance of the HWE-based biorefinery 3) Evaluation of the metrics for the environmental performance of the HWE-based biorefinery and 4) sustainability evaluation of HWE-based biorefinery using the evaluated risks, economic and environmental results.

3.3.1 Risk analysis and phased approach

3.3.1.1 Qualitative risk analysis

Considering the risks already explained in section 1.3.1, Table 3-1 presents a summary of the near-term market and technology risk analysis results related to each of the HWE-based biorefinery product option. As mentioned, the risk analysis in this step was conducted qualitatively and risk levels were defined as low, low to medium, medium, medium to high and high.

Implementation of an anaerobic treatment on the extracted hemicellulose stream and biogas production presented very low market risk since the biogas was considered to consume internally at the mill. In addition, the technology is well proven and the only challenge that might occur is due to the lack of enough experience related to the anaerobic digestion of hemicellulose streams. Therefore this product option involved minimum technology risk.

Regarding the animal feed option, the market associated with the sale of concentrated hemicellulose as an animal feed additive is fairly a large global market, having high price volatility. Therefore, it is essential to foresee the risks and probable discounts to local consumers in case of developing off-take agreements for this product. The major technical risk for this product was related to its concentration. At 70% concentration, which was essential for this application, the likelihood of having material handling problems, excessive high viscosity and even solidification of the product was high. Moreover, the product concentration stage was assumed to be performed within the mill’s existing evaporators. Due to the unique evaporator’s configuration and their current capacity also the high concentration level needed in the final output stream, this stage of the process was regarded as a main technology risk that was limiting the solid percentage of the marketable product.

Table 3-1 Near-term market and technology risk analysis for HWE-based biorefinery products

Product	Market risks	Qualitative score	Technology risks	Qualitative score
Biogas	Biogas would replace a portion of bark currently used in the mill boilers	Low	1.Well-proven technology 2.limited experience with hemicellulose	Low-Medium
Concentrated hemicellulose (70% solid for animal feed)	1.Selling price is dependent on product concentration 2. Many sellers in the market 3. High price volatility	Medium	Reallocation of unique configuration evaporators: 1. Available evaporator capacity 2. Liquor viscosity at high concentration	Medium
Acetate Salt (as de-icer)	1. Price depends on seasonal demand, winter severity. 2. Product Compostion; i.e. Formate content	Medium-High	1.Proven technology- API demonstration plant in Alpena-Michigan 2. Purification of the product might be required.	Low-Medium
Concentrated hemicellulose (50% dry solid for C5-sugars)	1. Transportation cost is dependent on product concentration. 2.Limited market volume with few manufacturing companies.	Medium	1. Required product concentration is achievable by using existing evaporators, minimum risk for evaporators.	Low-Medium
C5-sugars	1.Strong competition with China (supply & demand volatility) 2.Growing demand in N.A 3.Limited market volume with few manufacturing companies.	Medium	1. Complicated process (Enzymatic hydrolysis) 2. Complicated separation and purification units	Medium
Furfural	1. Strong competition with China 2. Early in N.A. market & growing demand in N.A.	Medium	1. Low process yield 2. Complex separation process	Medium

Acetate salt as a de-icer presented a high market risk associated with seasonal demand, variability in the required volumes on a yearly basis and the price volatility of the chemicals required for acetate salt production. Technology risk related to this product was low due to the proven production technology. However, in cases that the formate content of the product exceeds the acceptable limit, additional purification systems including extractive distillation is required.

In the product option related to selling of concentrated hemicellulose for C5-suagrs application, the market risks were at a medium level. Risks were mainly related to the agreements with the potential off-take partners regarding the transportation price of the product, as well as the limited market demand. On the other hand, technology risks associated with the evaporation were low to medium, due to the relatively low concentration rate of the product that was required for this option.

In the C5-sugars option, risk analysis results for sugar production illustrated that the market risk was at medium level. As previously explained, there are numerous producers located in Asia who play a large role in the current market. The global market size for C5-sugars is predicted to be 200,000 tons/year. The price volatility is attributed to the periodic overproduction of Chinese producers. Moreover, the current size of the C5-sugars market in North America is relatively small, with few manufacturing companies. Nonetheless, market growth potential is estimated to increase rapidly due to the growing demand. As for the technology risks associated with C5-sugars production, they were estimated to be medium as well. There were ambiguities regarding the enzymatic hydrolysis, separation and purification steps of the process, especially the presence of formic acid caused by weak acid separation that would threaten the product quality. Also, there is technology risks associated with the process scale-up to large-scale industrial projects.

Furfural option presented medium levels of risk for both market and technology. As stated before, Dominican Republic and China are the main producers of furfural in the global market. However, a growing market in North America, specifically at the pharmaceutical grade, will allow for better market penetration by local producers. Price volatility of furfural is very high due to the variability in Chinese supply. The major technology risk associated with this product was related to the low production yield, also separation and purification steps in the production process.

In addition to the risks that were identified for each product stream, the major technology risk related to the core business was the extraction rate of the hemicellulose. As explained earlier, high rates of extraction will result in significant loss in pulp mechanical strength and quality.

The results of the qualitative risk analysis were employed in defining the already explained phased-scenarios (Table 2-1).

3.3.1.2 Techno-economic assessment

For the biorefinery processes, there is a strong correlation between after-tax IRR and plant size; also the process complexity has a direct influence over the initial capital investment. Figure 3-2 presents the capital cost breakdown for the HWE-based phased scenarios. For the calculations of the installed equipment cost and total capital investment cost, the information presented in sections 1.4.2 and 2.4.2.1 were employed.

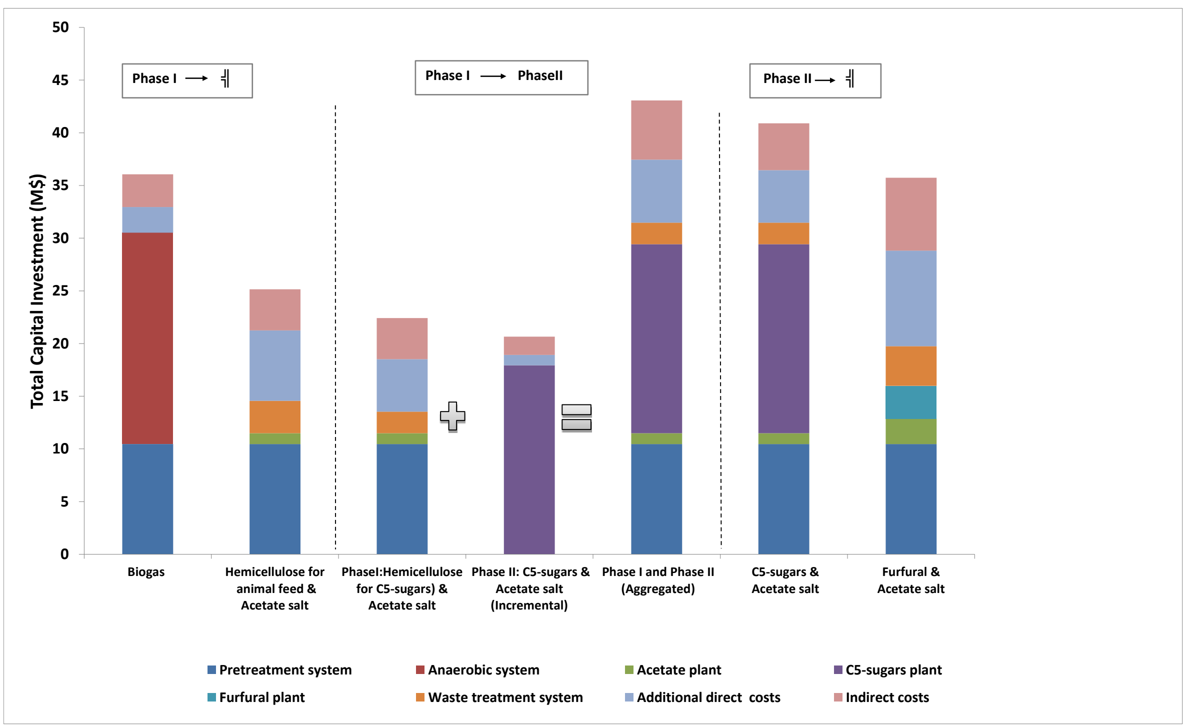

Figure 3-2 Capital cost breakdown for HWE-based process options

Operating costs were developed as the variable and fixed expenditures. Inputs for the operating cost were mass and energy balance results, financial data from the mill and information from the literature. Figure 3-3 illustrates the annual production cost breakdown for the HWE-based process options and the positive and negative costs.

Negative results represent the cost savings due to modifications in the mill's existing process, followed by implementation of the HWE-based biorefinery. Particularly, the biogas option presented a significant production cost credit due to the partial bark displacement at the mill's boilers. In other words, performing anaerobic treatment on the extracted hemicellulose stream and producing biogas contributed to the partial substitution of the bark that was required for the total steam production (total steam needed for the mill and biorefinery processes).

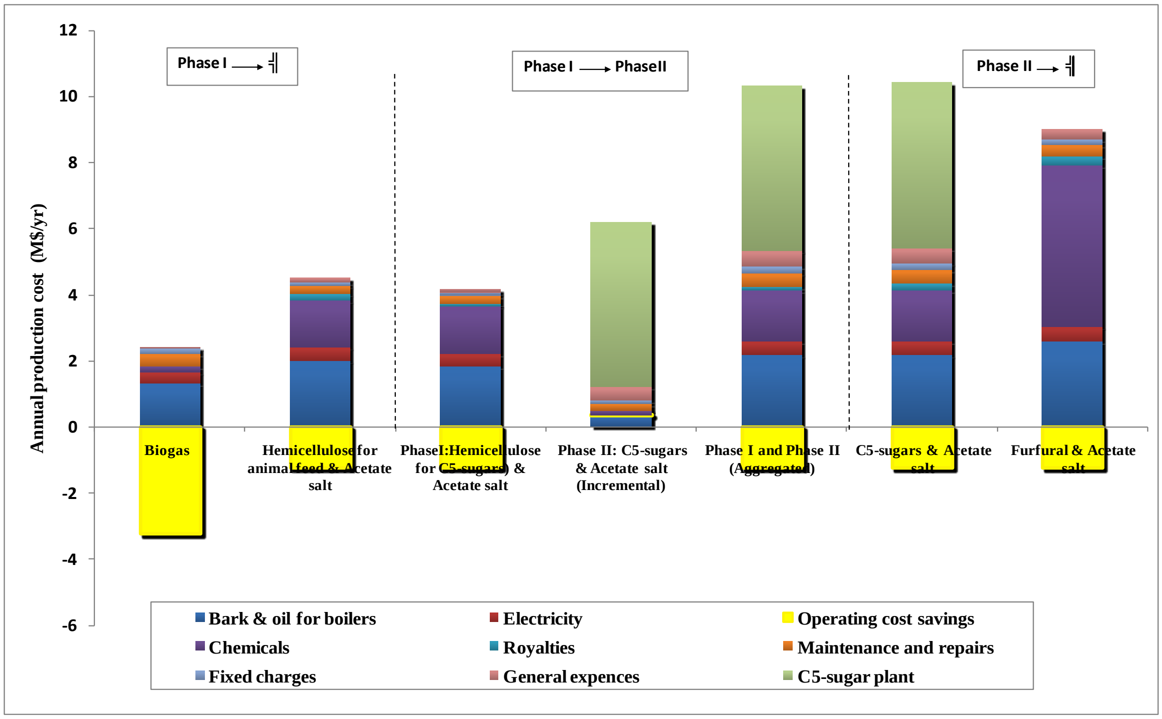

Figure 3-3 Annual production cost breakdown for HWE-based process options

Figure 3-4 presents the annual revenue breakdown for the defined HWE-based process options. The product selling price was set according to the market survey and information obtained from the literature. It is worth to highlight that product price for each HWE-based product included the cost related to the transportation of bioproducts from the mill to the potential customer. Considering the current pulping process at the case study mill, no additional wood feedstock was used in the biorefinery process. Woodchip savings were regarded as project revenues, since experimental data showed that at the extraction rate considered as the basis of the present calculations (10%), the overall mill's pulping yield would be improved. Pulp yield assumed to increase from currently 83.5% to future 90%, leading to 50 BDt/day of woodchips savings.

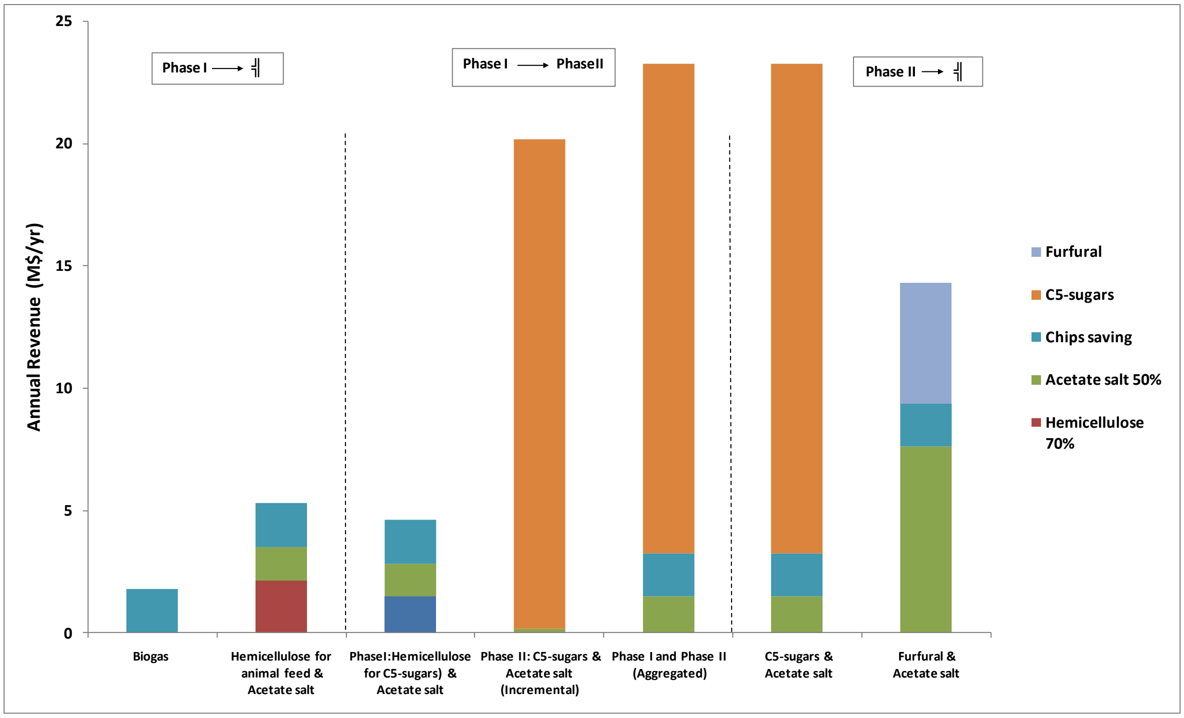

Figure 3-4 Annual revenue breakdown for HWE-based process options

A spreadsheet economic model was developed to calculate the cash flow of the biorefinery process options over the next 20 years. The biorefinery plant was assumed to construct over a two-year period. Process options in the phase I scenario were studied as a single investment project over the 20 year period. As well, for phase II process options in the third scenario, a single investment project over the 20 year period was considered. However, the design basis for the options in the second scenario was different. Phase I in this option was assumed to operate for 5 years and the products were sold to external customers during this period. In the third year of phase I production, construction of phase II was assumed to start. Afterwards, phase II production commenced and continued for the next 15 years. Figure 3-5 shows the cumulative cash flow related to the second scenario.

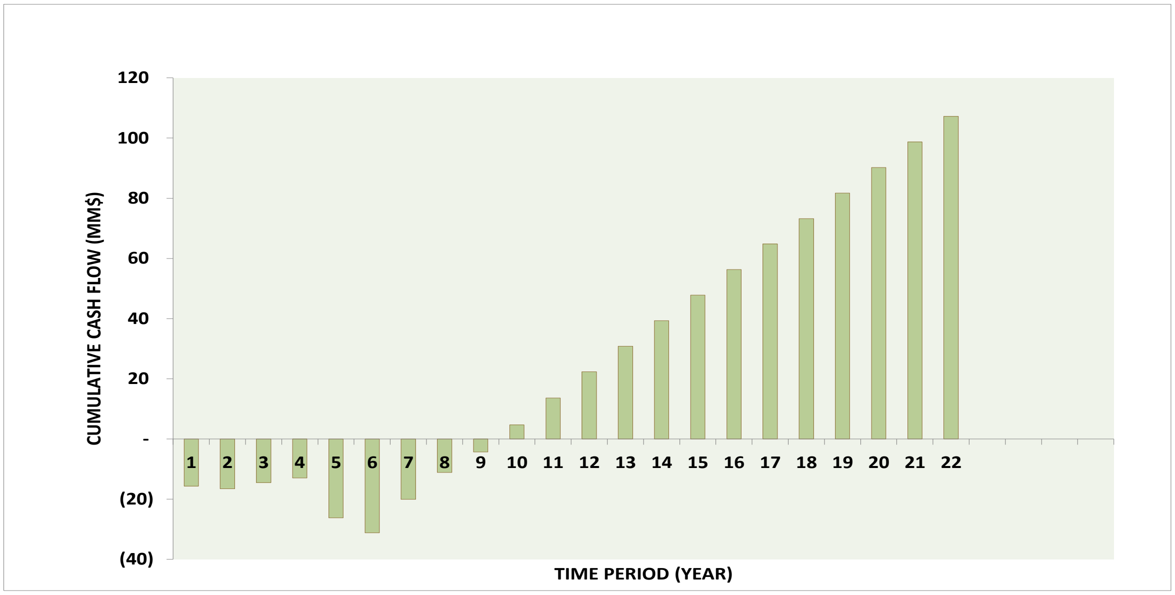

Figure 3-5 Cumulative cash flow distribution for investment phases in the second scenario

Figure 3-6 illustrates the calculated economic metrics and the overall economic performance of the three defined HWE-based phased scenarios and related process options.

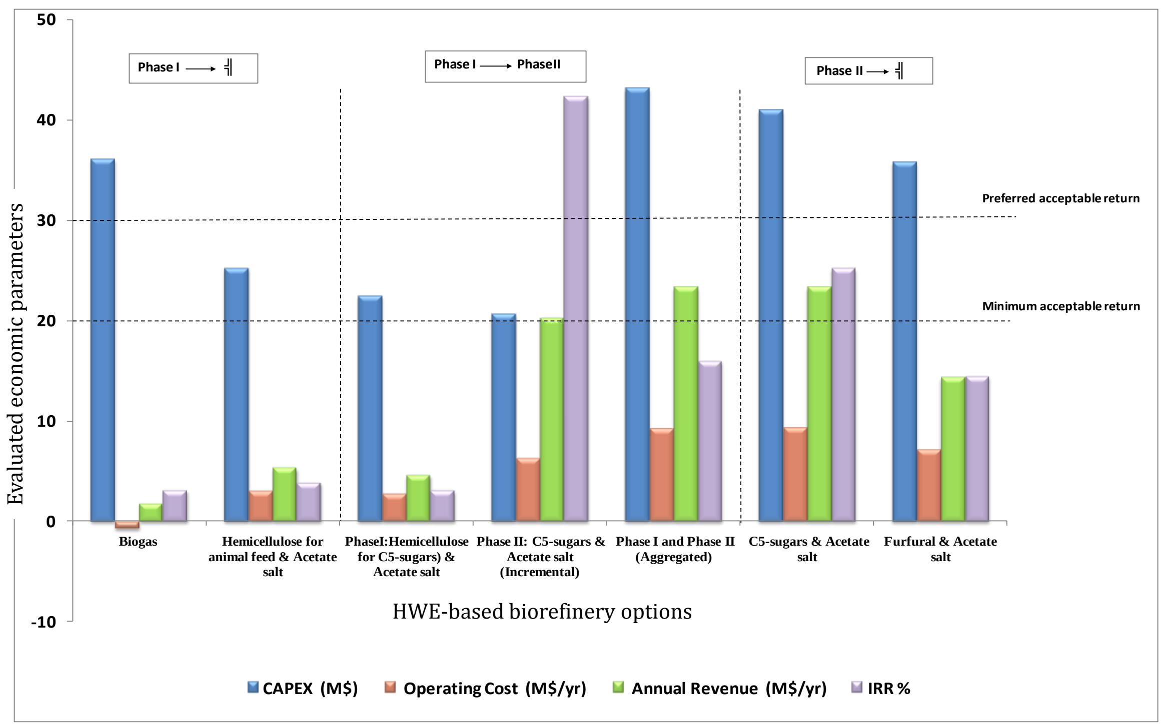

Figure 3-6 Overall economic results for HWE-based process options and phased scenarios

In this figure, the main economic results including capital investment, annual production cost, annual revenue and internal rate of return is illustrated. Due to having a relatively similar order of magnitude, all of the above-mentioned economic parameters are shown in the same graph. For the first scenario and regarding the biogas process option, it was assumed that the existing evaporators at the mill would be fully retired and biogas would displace part of the bark consumption in the boilers. However, since the investment cost associated with anaerobic digesters was high and the revenue was only related to the wood chips savings, this option presented the IRR of 3%. Process option related to concentrated hemicellulose for animal feed and acetate salt production did not present good economic results as well and had the IRR of 4%. Poor economic results of this option were due to high investment cost and low revenue from the products.

As for the third scenario and the process options that were defined to implement for the phase II of the project, the return on investment was considerably improved due to the production of added-value products. Considering the furfural and acetate salt option, the resulting IRR was shown to be 14%. Alternative process option in this scenario was the production of C5-sugars and acetate salt, directly after the hemicellulose extraction process. Analysis presented good economic results and acceptable profitability and this option contributed to the IRR of 25%, which is a favourable return on investment for the biorefinery projects. However, as mentioned earlier the market and technology risks associated with this alternative are high. In order to mitigate these risks and having the acceptable profitability, the second scenario was defined for the production of C5-sugars and acetate salt.

Three options were defined for the second scenario to illustrate the impact and benefits of phased implementation approach. In the first option, due to the relatively high investment cost and low product revenue, phase I resulted in a low IRR of 3%. For the second option, the incrementally favourable economic results of phase II provided an IRR of 42% that is the highest return among all the process options. For this option, the analysis was based on the economic assessment of incremental costs and revenues associated with the production of C5-suagrs and acetate salt for 20 years and costs of hemicellulose production in the previous phase were excluded from the economic assessment. The third option refers to the production of C5-sugars and acetate salt in two project phases. The design basis for this option was to produce hemicellulose for sale in phase I (for 5 years) and to vertically integrate C5-sugars production for 15 years in phase II (aggregated phase I and phase II). The economic results of this option were acceptable and the overall project IRR was 16%. In this particular option, it is expected that by the implementation of a phased approach, the technology and market risks associated with biorefinery integration will be significantly reduced.

Generally for successful strategic projects, a minimum IRR of 20% should be sought to maintain the minimum risks. However, projects with higher risk such as biorefinery technologies should aim for an IRR of more than 30%. Figure 3-7 presents the IRR results of all scenarios, with and without the inclusion of the government subsidy. A fixed subsidy of 15 million Canadian dollars, to be obtained from the Investments in Forest Industry Transformation (IFIT) program of Government of Canada, was considered for the biorefinery process options.

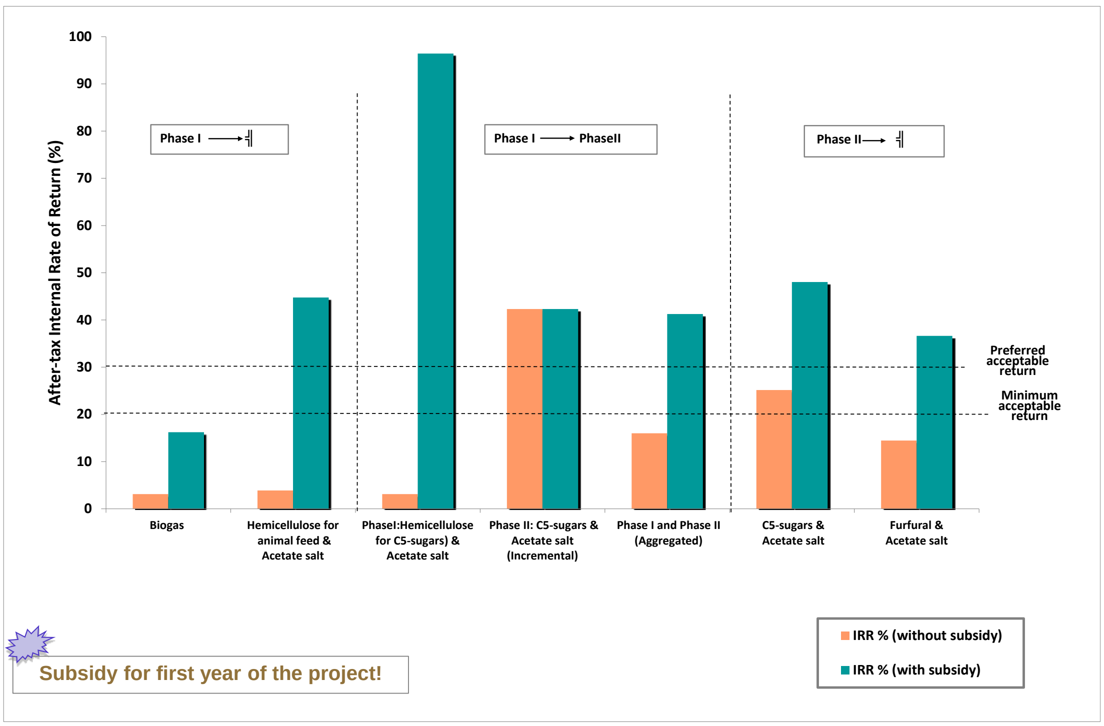

Figure 3-7 IRR results for the HWE process options, with and without subsidy

It was realized that IRR was particularly sensitive to subsidy, especially for lower capital cost projects. This in turn, implied subsidy's role to mitigate the financial risks associated with the biorefinery technologies. Especially in case of hemicellulose for C5-sugars and acetate salt production in phase I of the second scenario, IRR was found to change drastically, from 3% to 96%. Also, the aggregated option (phase I and phase II) presented interesting economic results after the inclusion of subsidy and the IRR was changed from 16% to 41%. However, this subsidy would be granted only for the first year of the project and particularly would not be applicable for phase II of the second scenario.

3.3.1.3 Sensitivity analysis

Following the preliminary identification of the technology and market risks associated with the HWE-based process options that were previously explained, major sensitive parameters with potential impact on the IRR were identified.

Table 3-2 Sensitive parameters, justification and variation ranges

Category	Sensitive parameters	Low value	High value	Base case	Justification
HWE Digester	Digester CAPEX	-	11.2 M$ (+20%)	9.3 M$	Possibility of capital cost increase due to unforeseen scope changes and limitations in available space at the mill.
Acetate salts	Acetate salts purification CAPEX	-	3.4 M$	0.9 M$	Purification system (extractive distillation) for removing the formate in the product
C5 sugars	C5 sugars production CAPEX	14.3 MM$ (-20%)	21.5 M$ (+20%)	17.9 M$	Possibility of capital cost changes due to unforeseen scope changes and complexity of the process
	C5 sugars production yield	60% (-25%)		80%	Possibility of decrease in process yield due to complicated process units (enzymatic hydrolysis, separation and purification units)
Anaerobic treatment	Anaerobic treatment CAPEX	20.7 M$ (-10%)	25.3 M$ (+10%)	23 M$	Possibility of capital cost changes due to complexity of the process
Furfural purification	Furfural purification CAPEX	3.96 M$ (-10%)	5.28M$ (+20%)	4.4 M$	Possibility of capital cost changes due to complexity of the process(purification system consisting of strippers, Decanters, Dehydrator and low boiling point column)
OPEX	Biomass for boilers	40 $/BDt (-20%)	60 $/BDt (+20%)	50 $/BDt	Price volatility and trend for required bark for boilers
	Sulphuric acid price	100 $/t	205 $/t	150 $/t	Price volatility for chemicals (required acids for hydrolysis)
	Chemical (hydroxide)	631 $/t (-25%)	1052 $/t (+25%)	842 $/t	Price volatility for chemicals (hydroxide)
	C5 sugars OPEX	400 $/t (-20%)	600 $/t (+20%)	500 $/t	Many external factors (enzyme, fuel price,etc.) may change the operating cost.
Revenue	Wood chips Biomass savings	80 $/BDt (-20%)	120 $/BDt (+20%)	100 $/BDt	Price volatility and trend for feedstock wood chips
	Acetate salts price	2.9 $/Us gal (-10%)	4.55 $/US gal (+40%)	3.25 $/US gal	Price depends on seasonal demand, winter severity and product composition.
	hemicellulose selling price		152 $/t	103 $/t	Price depends on product concentration and market negotiations
	C5 sugars price	1800 $/t (-10%)	2400 $/t (+20%)	2000 $/t	Growing demand in N.A. and supply and demand volatility
	Furfural selling price	800 $/t (-20%)	1600 $/t (+60%)	1000 $/t	Range of furfural selling price for industrial and pharmaceutical applications

Table 3-2 illustrates sensitive parameters and their variation ranges. In the context of the sensitivity and scenario analysis, following parameters were chosen: CAPEX, OPEX, product selling price and process parameters (e.g. yield). Table 3-3 presents the sensitive parameters that were selected for the sensitivity and scenario analysis of each HWE-based biorefinery option.

Table 3-3 Sensitive parameters for sensitivity and scenario analysis

RISK parameters	Biogas	Hemis for animal feed & A.S	Phase I: Hemis for C5-sugars) & A.S	Phase II: C5-sugars & A.S (Incremental)	Phase I and Phase II (aggregated)	C5-sugars & A.S	Furfural & A.S
Digester CAPEX	X	X	X	-	X	X	X
Acetate salts purification CAPEX and OPEX	-	X	X	X	X	X	X
C5 sugars production CAPEX	-	-	-	X	X	X	-
C5 sugars production yield	-	-	-	X	X	X	-
Anaerobic treatment CAPEX	X	-	-	-	-	-	-
Furfural purification CAPEX	-	-	-	-	-	-	X
Biomass for boilers	X	X	X	X	X	X	X
Sulphuric acid price	-	-	-	-	-	-	X
Chemical (hydroxide)	-	X	X	X	X	X	X
C5 sugars OPEX	-	-	-	X	X	X	-
Wood chips Biomass savings	X	X	X	-	X	X	X
Acetate salts price	-	X	X	X	X	X	X
hemicellulose selling price	-	X	X	-	X	-	-
C5 sugars price	-	-	-	X	X	X	-
Furfural selling price	-	-	-	-	-	-	X

Figure 3-8 to Figure 3-10 demonstrate the results of the sensitivity analysis for the process options that were defined for the second scenario. In regards to phase I of this scenario, i.e. concentrated hemicellulose for C5-sugars and acetate salt, profitability of the project was greatly sensitive to increased CAPEX if acetate salt purification was required, and under-estimated CAPEX for the HWE digester. However, risks associated with the former parameter were believed to be low. Also, in the case with financial subsidies, the impact of these two parameters, and their variation, was considerable. Moreover, increase in the price of chemicals (hydroxide) that was used in acetate salt production (OPEX parameter) and a decrease in wood chips price (revenue item due to pulping yield improvement) had negative impacts on internal rate of return.

Results of the analysis proved that the project profitability was highly dependent on the negotiated selling price of the concentrated hemicellulose and acetate salt. It should be noted that downside and normal IRR must be around the preferred acceptable range, which was defined to be 25% in this study. In case of this process option, the normal, downside and even upside IRR were lower than minimum acceptable range (11%). However, with inclusion of the government subsidy, it was proved that project profitability could reach higher than the preferred acceptable level.

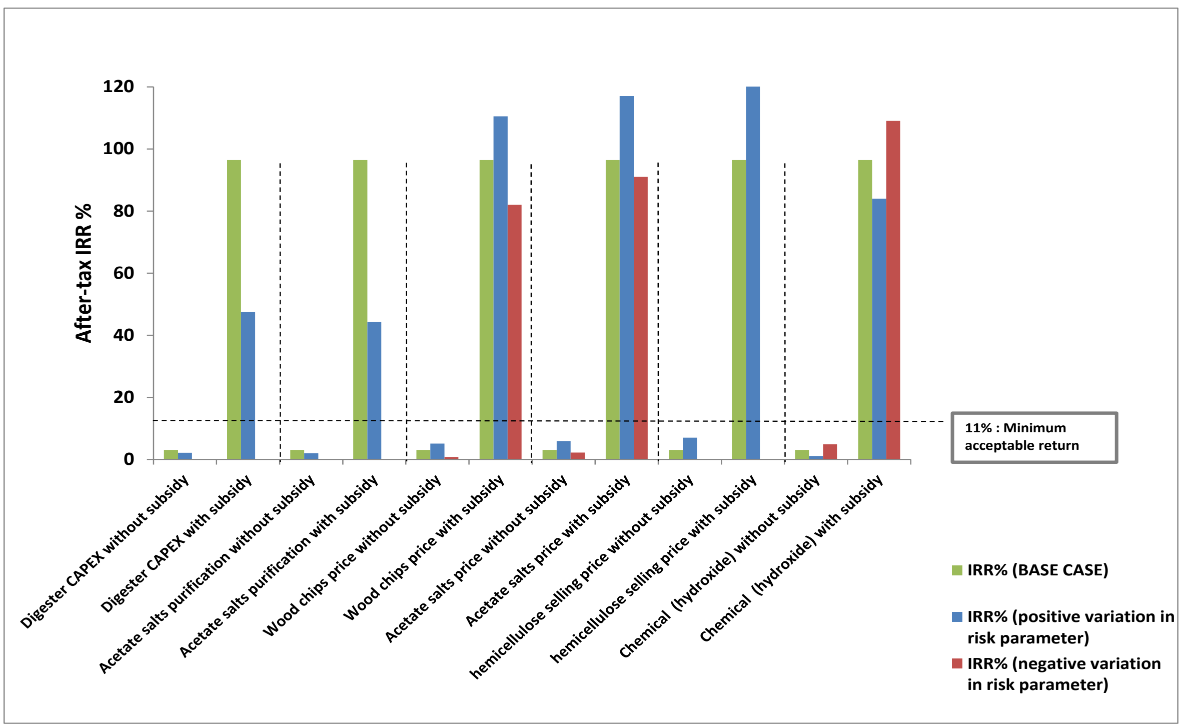

Figure 3-8 Sensitivity analysis results for hemis for C5-sugars & A.S. in phase I

Figure 3-9 presents the sensitivity analysis results for the second process option of the second scenario (incremental production of C5-sugars and acetate salt). IRR was sensitive to the decrease in C5-sugars production yield. C5-sugars process was regarded to be complex, due to complicated separation and purification units; also the enzymatic hydrolysis step had a significant impact on the process yield. In addition, IRR was sensitive to underestimated CAPEX for C5-sugars production and increase in C5-sugars production cost. Project profitability was considerably dependent on the negotiated selling price of C5-sugars and results proved that IRR could become interesting for increased product selling price.

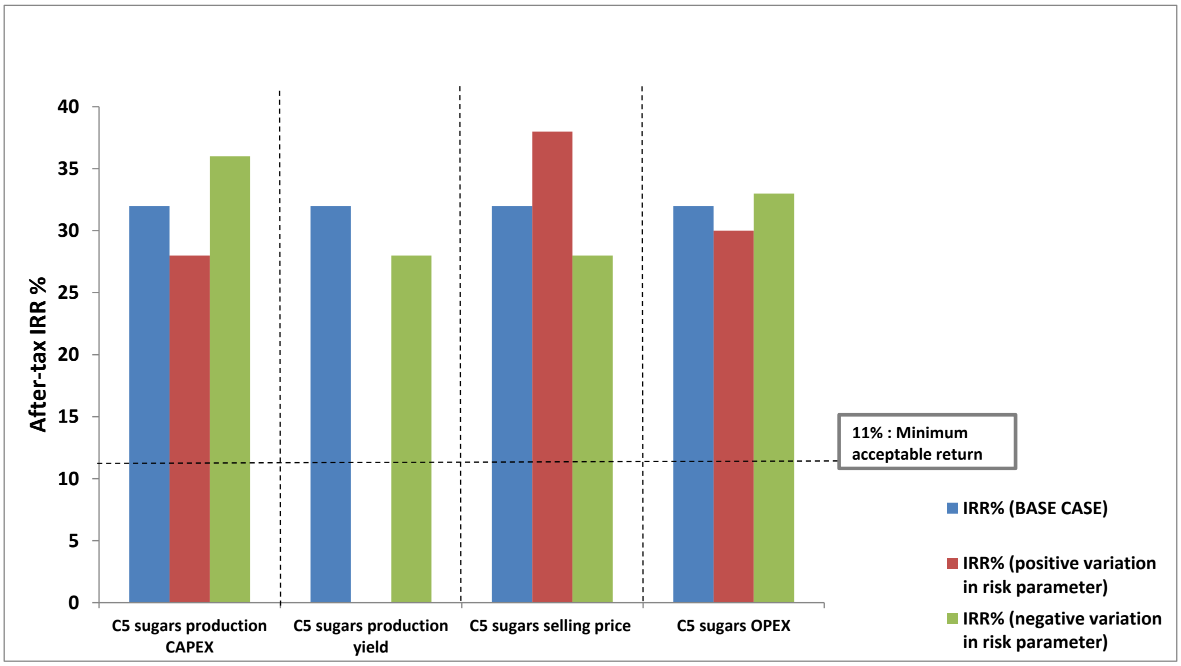

Figure 3-9 Sensitivity analysis results for C5-sugars & A.S. in Phase II (Incremental)

Considering the third process option (acetate salt and hemicellulose for C5-sugars in phase I and acetate salt and C5-sugars in phase II) and according to the results presented in Figure 3-10, the profitability of the project was highly dependent on the revenue from the product streams in each phase. This in turn, implied the role of having negotiations over the product selling price also concrete off-take agreements prior to implementation of a biorefinery project. According to the presented results, IRR was negatively affected by the decrease in C5-sugars production yield. Moreover, under-estimated CAPEX for C5-sugars and increase in its production cost played a great role in profitability decrease.

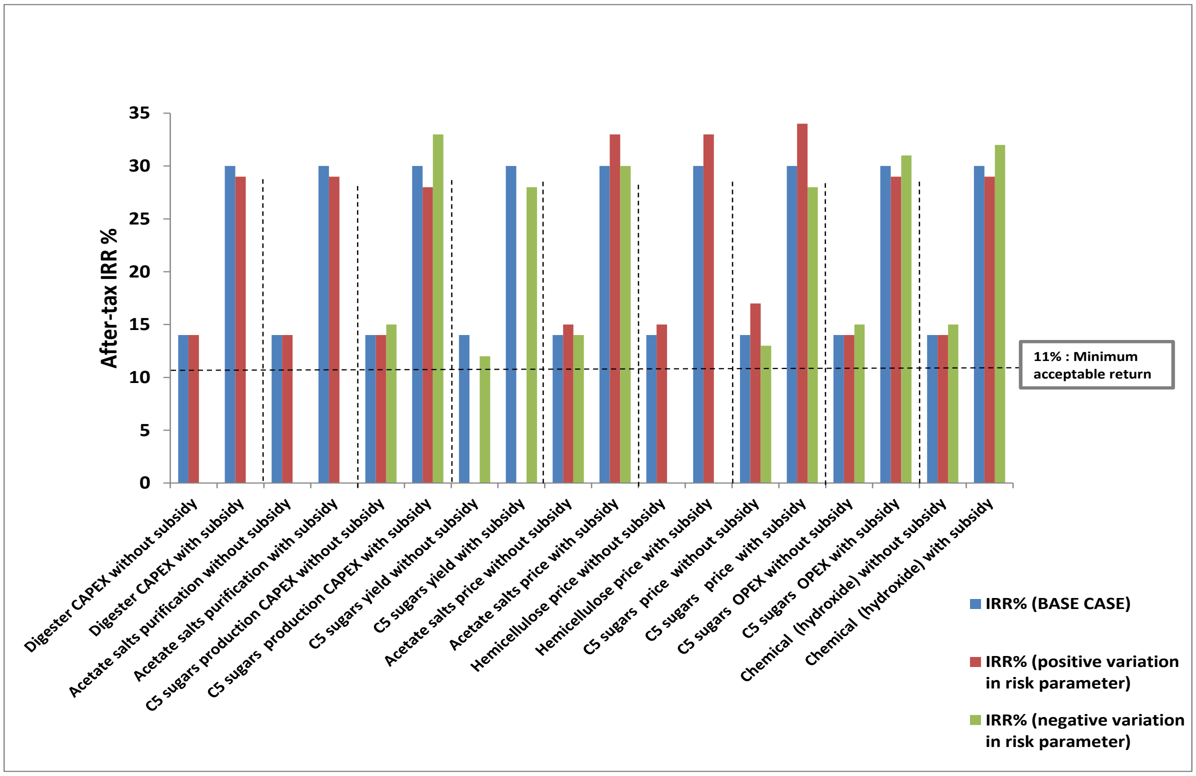

Figure 3-10 - Sensitivity analysis results for Phase I and Phase II (Aggregated)

As the next step of sensitivity analysis, scenario analysis for each HWE-based biorefinery option was conducted to imply the impacts of variations in all the selected sensitive parameters on the economic profitability. In this step, the conversion factors that were defined in Table 2-3, qualitative market and technology risks (Table 3-1) and sensitive parameters (Table 3-3) were used.

The difference between the IRR for the basecase and worstcase scenarios were evaluated and presented in Figure 3-11. As seen in the results and with including the government subsidy, in the case of aggregated phase I and phase II, the IRR was least impacted by the simultaneous occurrence of the sensitive parameters; IRR difference between basecase and worstcase was calculated to be 11%. On the contrary, hemicellulose for C5-sugars and acetate salt presented the highest IRR reduction of 61%, when compared with other HWE-based biorefinery processes. Scenario analysis results show that occurrence of all the sensitive parameters simultaneously, led to adverse effects in the economic profitability of low capital costing projects. Regarding the process options for the third scenario, i.e. acetate salt and C5-saugars and acetate salt and furfural, the IRR difference was calculated to be 16 % and 19% respectively.

Scenario analysis results implied the importance of phased approach and the fact that incremental implementation of the C5-sugars biorefinery is less sensitive to risk parameters when compared to single-phased implementation of the same process option.

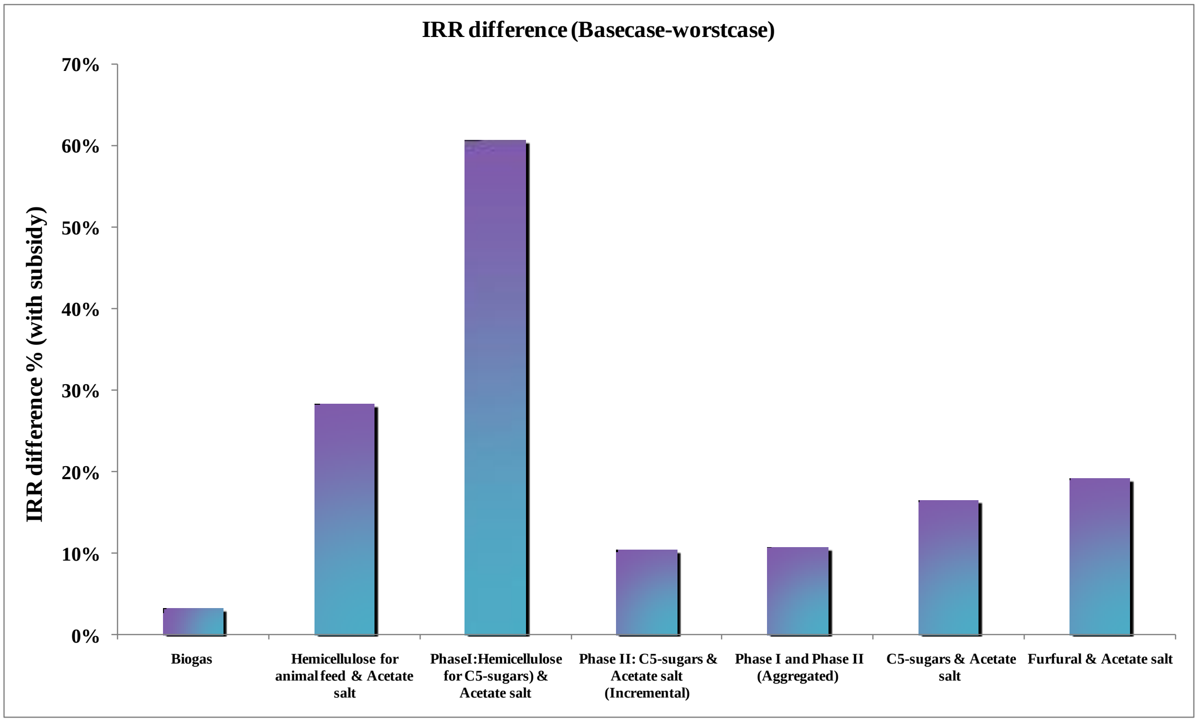

Figure 3-11 Scenario analysis, IRR differences of base case and worst-case scenarios

3.3.1.4 Conclusion

Investing in the transformation of the forest industry into a biorefinery involves managing several risks. This study concludes that the margins to the forestry company increased significantly by going to C5-sugars from hemicellulose and this was not taking into account further subsidy from the implementation of the second phase of the project. Results proved that the most recommendable option was the second scenario, which aggregated production of acetate salt and concentrated hemicellulose for C5-sugars in phase I and C5-sugars and acetate salt in phase II. In this option, not only was the overall IRR acceptable (16%), but due to the implementation of the phased approach, it was the best choice in terms of risk mitigation over time. For the first scenario, the process options presented poor economic results and IRR related to the Biogas and hemicellulose for animal feed options were 3% and 4%, respectively. Moreover, process-product options for the third scenario, i.e. C5-sugars and acetate salt and furfural- acetate salt in phase II presented good financial results, compared with the other strategies, by having an IRR of 25% and 14% respectively. However, the market and technology risks associated with these options were relatively high. In addition, government subsidies significantly decrease the financial risks associated with process options in this project, in particular for the IRR which was found to be very sensitive to subsidy. For the hemicellulose for C5-sugars and acetate salt option, by implementing government subsidy, IRR was found to change considerably from 3% to 96%.

3.3.2 Environmental analysis

Following implementation of the LCA methodology, the inventory data including the material input and emissions into water, air and soil were employed for the characterization and evaluation of the environmental impacts. In this assessment, four endpoint impact categories including climate change, human health, ecosystem quality, and resources were considered. Calculated LCA parameters are explained in section 2.4.3.7.

Generally, midpoint impact categories are mostly preferred for hotspot analysis; nonetheless, in this study endpoint impact categories were presumed to be an adequate basis to illustrate the overall environmental performance of different HWE-based biorefinery alternatives for strategic decision-making purposes.

It is necessary to highlight that the phased approach implementation was not considered in the environmental analysis since LCA evaluates the long-term environmental results. In other words, including the time aspect in the LCA analysis was not pertinent.

3.3.2.1 Consequential LCA results

Breakdown of the ‘cradle to gate’ environmental results related to HWE-based production pathways are shown in Figure 3-12 to Figure 3-15. Analysis of the model behind the results reveals that the differences in environmental impacts of defined biorefinery options can be explained by: 1) differences in energy consumption, particularly bark utilization for providing steam, also electricity consumption; 2) differences in types and quantities of chemicals and consumables such as sulphuric acid, enzyme, and lime; 3) differences in production capacity of each biorefinery option that contributes to different bioproduct transportation results.

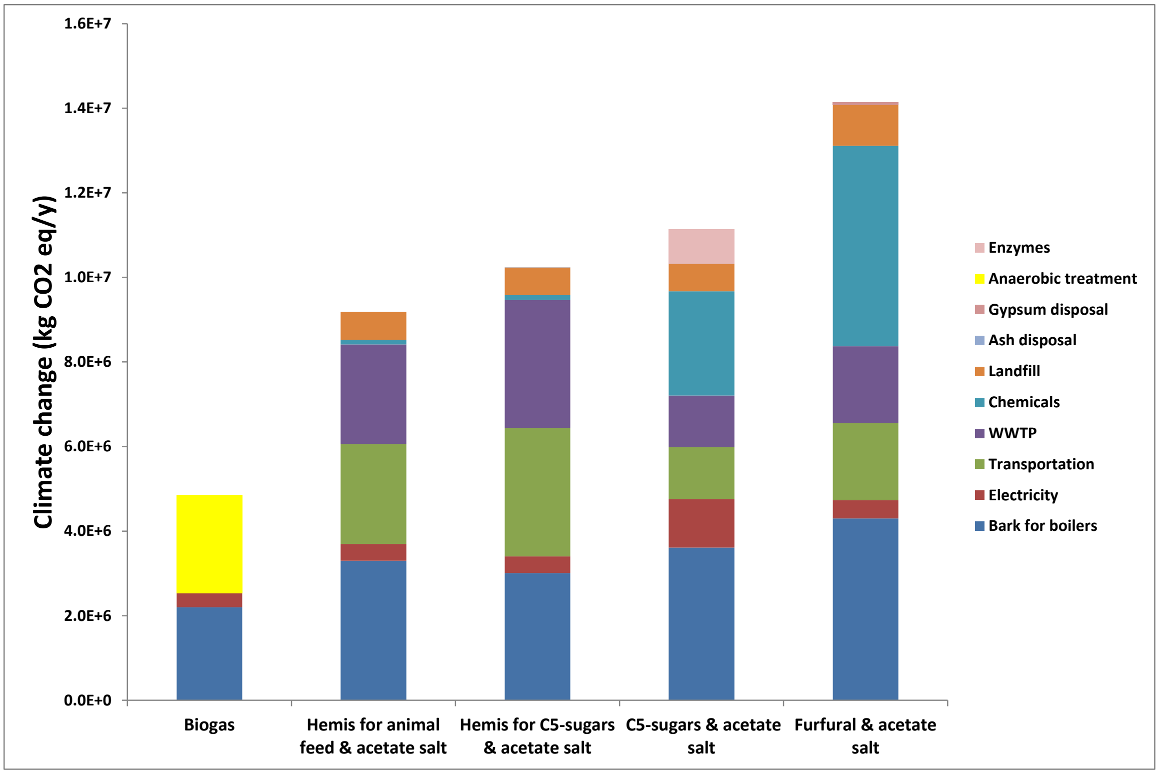

Figure 3-12 Climate change impacts of HWE-based biorefinery options

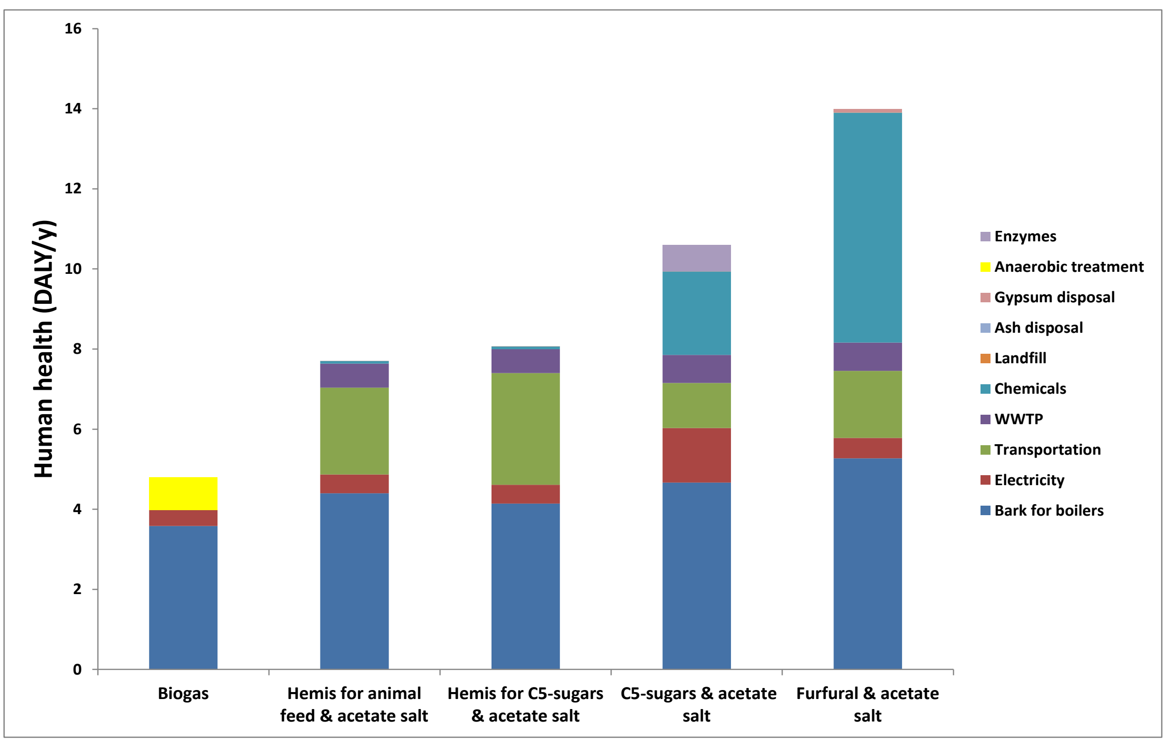

Figure 3-13 Human health impacts of HWE-based biorefinery options

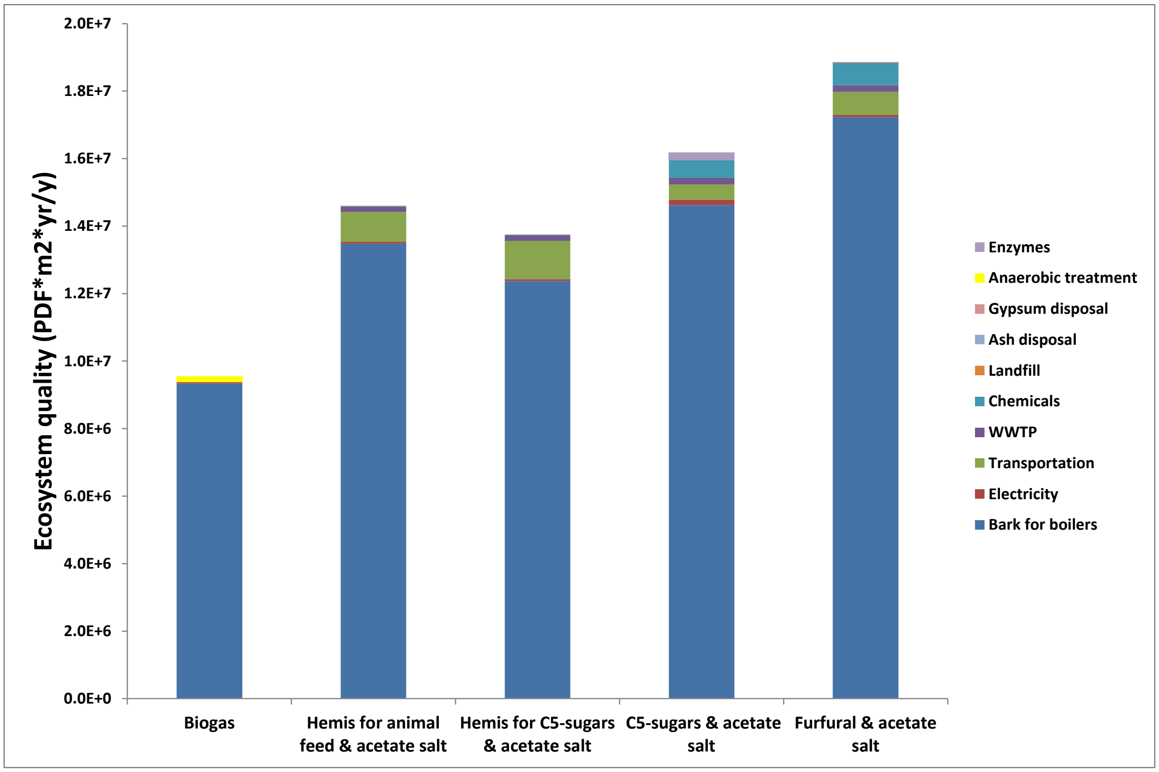

Figure 3-14 Ecosystem quality impacts of HWE-based biorefinery options

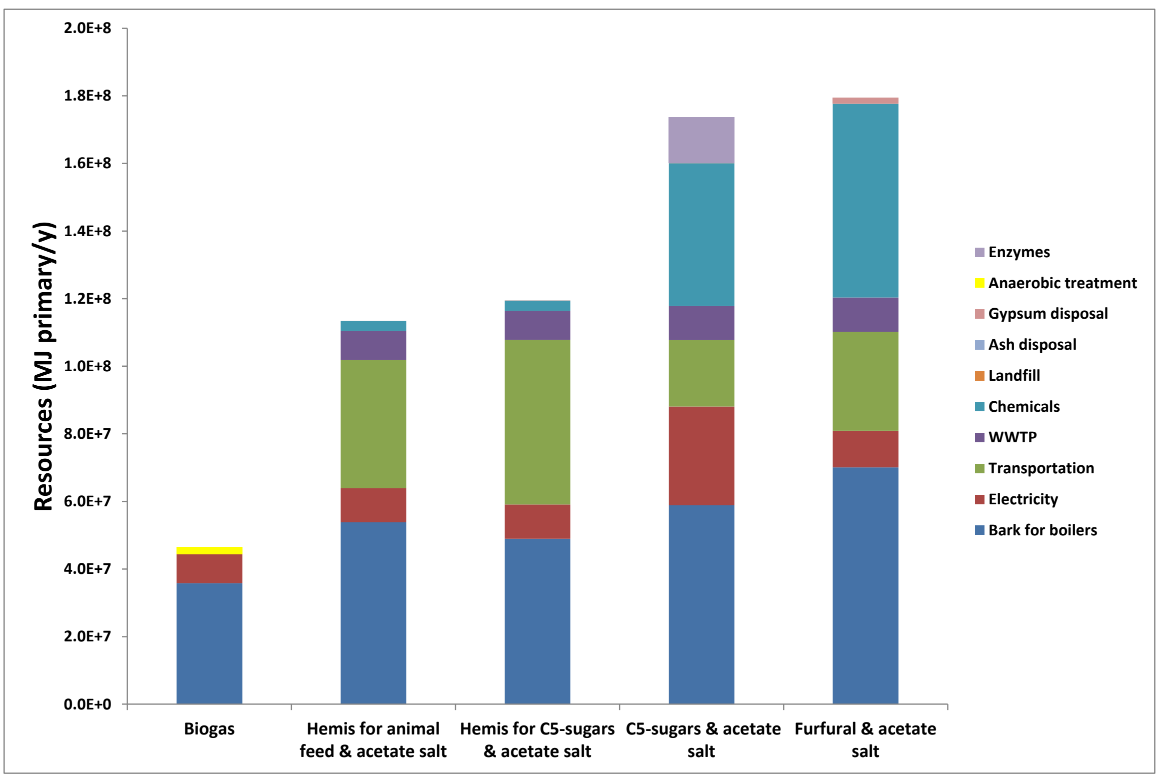

Figure 3-15 Resource consumption impacts of HWE-based biorefinery options

Following a detailed energy analysis and considering the complete integration of biorefinery to the P&P mill (in terms of mass and energy), steam and electricity requirements for the mill and biorefinery processes were evaluated and incremental energy demand due to biorefinery implementation was calculated. Energy Island at the existing mill consisted of two types of boilers for the steam production, which used biomass and oil as fuel sources. In this evaluation, it was assumed that bark boilers would exclusively be responsible to provide the additional required steam for the biorefinery processes. Furthermore, for the mill pulping process, energy policy to provide steam would remain the same as before the biorefinery implementation. In other words, both oil and bark would be the fuel sources to provide energy for the pulping production lines. Consequently, and due to the cut-off procedure already explained, the particular environmental impacts related to steam procurement for the case study mill including oil extraction, transportation and burning at the oil boilers, also the bark acquisition and burning at bark boilers were excluded from the LCA system boundary. Table 3-4 presents the annual production capacity of the defined HWE-based biorefinery production pathways, as well as the bark consumption in order to provide incremental required steam for different biorefinery option.

Table 3-4 Production capacity of HWE-based options & incremental required bark

	Biogas	Hemicellulose for animal feed and acetate salt	Hemicellulose for C5 sugars and acetate salt	C5 sugars and acetate salt	Furfural and acetate salt
Production capacity	$5.2x10^6$ m^3/yr	Hemis (70%): 22000 t/y A.S.: 2400 t/y	Hemis (50%): 29000 t/y A.S.: 2400 t/y	C5-sugars: 10000 t/y A.S.: 2800 t/y	Furfural: 5000 t/y A.S.: 14000
Required bark for biorefinery (BDt/day)	77	116	106	127	151

Based on the process design, biogas would partially substitute bark consumption at the existing boilers and resulted in lower steam and bark demand, when compared with other options. On the contrary and following the energy balances, total bark consumption for the furfural and acetate salt production process was evaluated to be approximately 151 BDt/day, which was higher compared with other process alternatives. Most of the steam consumption for this process was related to stripping columns for the furfural purification. Furthermore, steam demand for the C5-sugars and acetate salt option was relatively high due to energy consumption for the enzyme production to be used in enzymatic hydrolysis. This process was energy intensive and energy was considered in terms of required steam as energy carrier.

It was assumed that burning barks at the existing bark boilers was nearly a carbon neutral process, i.e. CO_2 that was generated from combustion of barks was considered as biogenic CO_2. Examples of biogenic CO_2 emissions include but are not limited to CO_2 from the combustion of biogas, CO_2 generated from the biological decomposition of waste in landfills and wastewater treatment, CO_2 resulted from combustion of biological material, including all types of wood and wood wastes, forest residues, and agricultural materials (U.S.Env., 2011). However, whole life cycle of the bark as the main energy source could not be considered as a completely carbon-neutral process. Although the biomass-harvesting step was presumed to perform sustainably, there were still significant emissions resulting from processing and transportation of bark to the mill's site. While CO_2 emissions from the bark combustion were considered as zero, the whole life cycle of bark has to be included in the environmental analysis. Consequently, it was proved that barks procurement and transportation was one of the most important process parameter that contributed to major environmental impacts, particularly the resources consumption.

Similarly, the incremental electricity demand due to biorefinery integration was evaluated and according to the results, the calculated power consumption of all the HWE-based biorefineries was relatively the same. However, in comparison with the defined biorefineries, C5-sugars process was the significant power consumer due to the additional electricity demand for the enzyme production. Data regarding the electricity consumption for the enzyme process was provided from literature review. For modelling the electricity consumed by different processes in the life cycle, data from the current average Quebec electricity supply was used.

Total chemical consumption in the furfural and acetate salt biorefinery strategy was higher than other HWE biorefinery options; dilute acid hydrolysis for the furfural production process consumed high volume of sulphuric acid as the main chemical. In addition, due to higher acetic acid production rate in this option, the required hydroxide for acetate salt process was higher, when compared with other alternatives. However, HWE biorefinery implementation resulted in minor changes in the P&P process and in particular decreased the consumption of some chemicals. The chemical savings of the existing mill, due to biorefinery integration, were considered as the avoided consumables in the defined system boundary.

Regarding the enzymes that were used in the enzymatic hydrolysis for C5-sugars production and based on the optimal process design, it was assumed that the enzyme production plant would be co-located at the HWE biorefinery and the existing mill. In this case, electricity and other consumables would be easily provided for the enzyme production from the on-site facilities. A sensitivity analysis proved that off-site production of enzymes would have significant environmental impacts, particularly from the viewpoint of enzyme transport and raw materials consumption.

River water considered to be used as the water source for the biorefinery process options. River flows are resources that are constantly regenerated, however, still there is no consistent and clear metric for this type of resources and clear damage factors have not been calculated for them (Koehler, 2008). Consequently, impacts related to water withdrawal and turbined water was disregarded in this analysis; these impacts were mainly included in the foreground system and characterized by the resource consumption.

Simple transportation model was employed in this analysis. It was assumed that the distance ranges were between 120 km and 500 km for the transport of biorefinery products to the targeted potential customers. For the barks used in the existing boilers, a transportation distance of 100 km to the mill was considered.

Consequential environmental analysis demonstrated favourable results for the biogas option since biogas would partially substitute bark consumption at the existing boilers. Therefore, due to its internal application at the mill, no environmental impact resulting from bioproduct transportation was considered for this option. In addition, CO_2 that generated from biogas combustion was considered as biogenic one. Conversely, anaerobic processing for the biogas production contributed to a relatively high impact on the climate change results.

Hemicellulose for animal feed and hemicellulose for C5-sugars have relatively similar production capacities therefore; there is no considerable difference between them in terms of the evaluated environmental results. Also, due to the higher load of effluent streams to the existing-modified wastewater treatment plant, impacts associated with effluent treatment were significant the main difference between these options corresponded to the additional required steam to concentrate the extracted hemicellulose from 50% to 70%, by re-allocated multi-effect evaporators.

For the C5-sugars and acetate salt and due to the additional steam requirement for the enzymatic hydrolysis, impacts resulted from bark consumption were substantial. Microbial components and electricity consumption for the enzyme production and the consumed chemicals were recognized to be the key contributors in the environmental results attributed to this process option. Consequential LCA results revealed that furfural and acetate salt production contributes to substantial environmental impacts. Following the energy balances, this option required more steam for furfural purification. For this process option, chemicals demand, including sulphuric acid for dilute acid hydrolysis and lime for gypsum removal played a significant role in the evaluated environmental impacts, particularly on the climate change and human health.

3.3.2.2 Overall LCA results

Subsequent step in the LCA analysis was to incorporate the environmental impacts associated with displaced processes and competing products. Breakdown of the overall environmental results and the relative contribution of each HWE-based biorefinery option along with displaced process/products to the end-point impact categories are presented in Figure 3-16 to Figure 3-19. For the purpose of modelling and calculations, negative values of the inventories were considered for displaced products and processes. Thus, negative bars represent the impacts of these processes while positive bars are related to the consequential impacts of HWE-based biorefineries.

Regarding the required biomass for the biorefinery and as explained before, production capacity of the existing mill is 600 BDMt per day of pulp and the pulping line produced high-yield pulp (approximately 84%) from a mixture of hardwoods. Considering the current pulping process at the case study mill, not only no additional woodchips feedstock was consumed in the HWE-based biorefinery process, but also the biorefinery implementation resulted in incoming wood chips savings of approximately 50 BDt per day.

Considering the competing products, identification of products that are likely to be substituted or displaced by biorefinery products is a critical step in the life cycle inventory and system boundary definition. It is important to note that a product might have multi-functions and different applications that result in different goals and environmental results in the LCA studies. While selecting a product substitute, major aspects needed to be taken into consideration; Main function of the competing product, identification of the market sector that will be affected by the new product and properties that improve the market position of the bioproduct relative to the competing products (Ekvall and Weidema, 2004).

In this study, competing products considered as those that were produced from fossil or agricultural resources. In addition, bioproducts entering the market were assumed to displace an equivalent quantity of functionally equivalent products from alternative production routes. Therefore, equivalency ratio was defined in order to calculate the substitution quantities of displaced products. These products were modeled, using the existing proxies in the SimaPro software. Table 3-5 presents the HWE-based biorefinery products resulting from same rate of the extracted hemicellulose stream and the competing products.

Table 3-5 Biorefinery products and competing products

Biorefinery product	Production capacity	Competing product	Equivalency ratio	Remarks
Biogas	5.2 x 10^6 m3/yr	Bark for Boilers	28 BDt/day Dry bark, Same	100% of biogas replaced part of bark at the boilers
Acetate salt	2400 t/y & 14000 t/y	Acetate salt from methanol carbonylation	1 Same product	Well-known industrial process, Methanol was produced from natural gas
Hemis for animal feed (70%)	22000 t/y	Molasses (72%) from sugar beet	1 Same product	Molasses was a by-product of crystallization process of sugar juice at the sugar refinery
Hemis for C5-sugars (50%)	29000 t/y	Sugar from sugar cane	1.6 Same functionality	Sugar displaced by xylitol, with the same sweetness. Considering 40% reduction in absorbed calories
C5-sugars	10000 t/y	Sugar from sugar cane	1.6 Same functionality	Sugar displaced by xylitol, with the same sweetness .Considering 40% reduction in absorbed calories
Furfural	5000 t/y	Phenol	1.1 Same functionality	Phenol and furfural as usual solvents for extraction of lubricating oil

Sugar from sugarcane was selected as the competing product for hemicellulose for C5-sugars and for the C5-sugars biorefinery products. Process yield for the production of C5-sugars was taken into account for calculating the amount of substitute products. According to a detailed market survey, the targeted application for these biorefinery products was for xylitol production. Sugar has been one of the most important components of the human diet due to its energy contribution with the capacity to sweeten. Xylitol as a functional sweetener has the same sweetness as regular sugar; however, the absorbed calorie of xylitol is 40% less than that of the regular sugar, improving its functionality especially for the diabetics and for preventing obesity. In order to maintain the same functionality, the equivalent sweetness to intake-calorie ratio was considered as the basis for comparison.

Furfural is a chemical that can be used for the several applications including Recovery of lubricants from cracked crude, feedstock for the production of furan resins, also called furfuryl alcohol resins and flavour compound. Following market analysis, an interesting application for furfural identified to be as a solvent for lubricating oil extraction. In addition, phenol was recognized to be the chemically equivalent product to furfural with the same functionality (Mohammed and Kheder, 2009). For calculating the functionality equivalencies, the raffinate yield and solubility of both solvents were considered and the ratio was calculated to be 1.1.

For the transportation of the competing products, a distance between 600 km to 3000 km was assumed. Regarding sugar as the substitute product for hemicellulose-based-sugars options, it was assumed that sugarcane would be transferred from Brazil to a potential sugar refinery located in Montreal. The transportation means for this case was assumed to be barge. The transportation of other products was considered relying mainly on trucking.

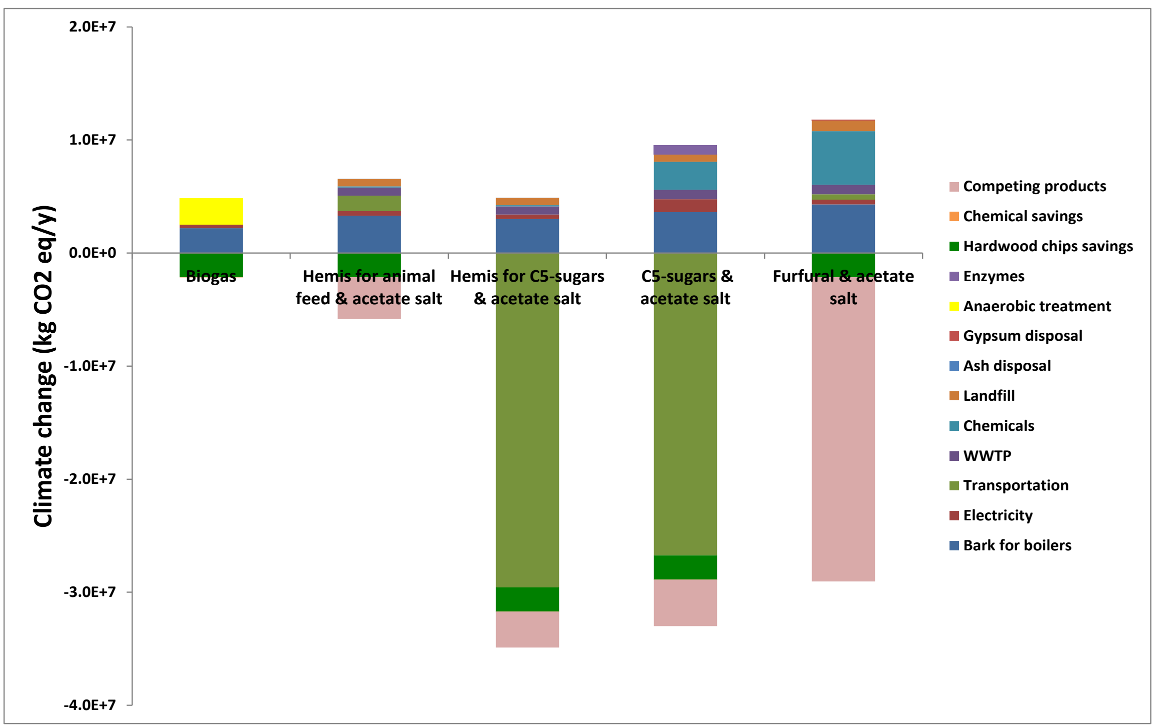

Figure 3-16 Overall climate change impacts related to HWE-based biorefinery options

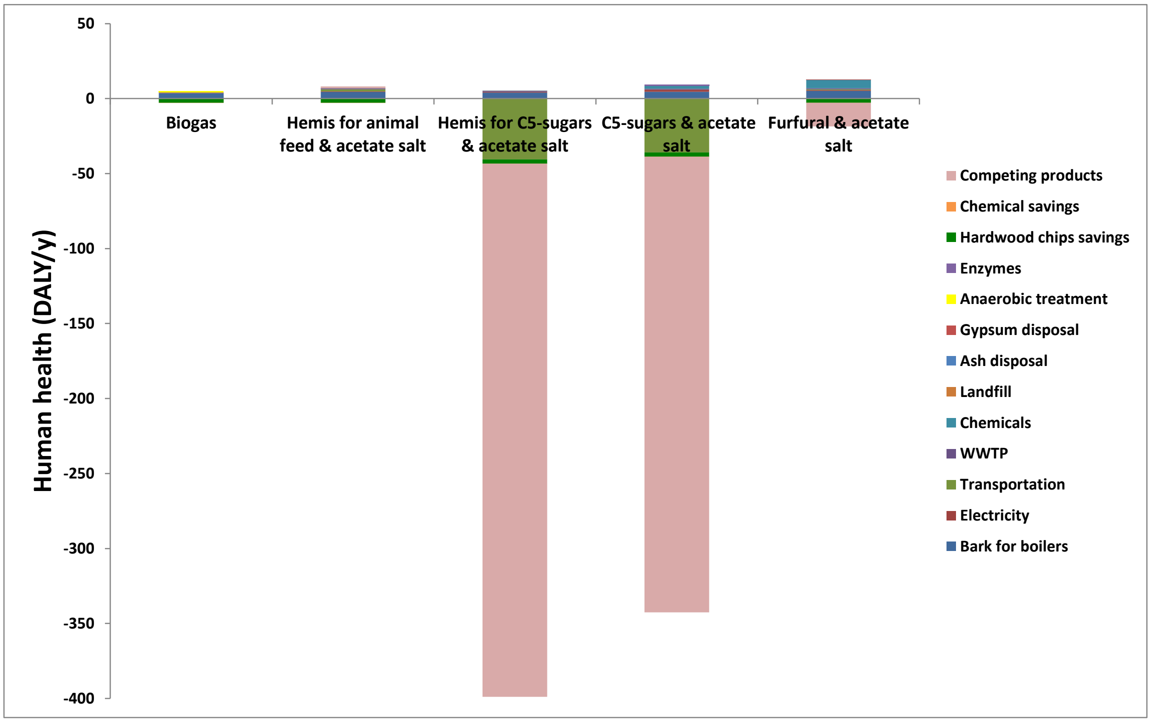

Figure 3-17 Overall human health impacts related to HWE-based biorefinery options

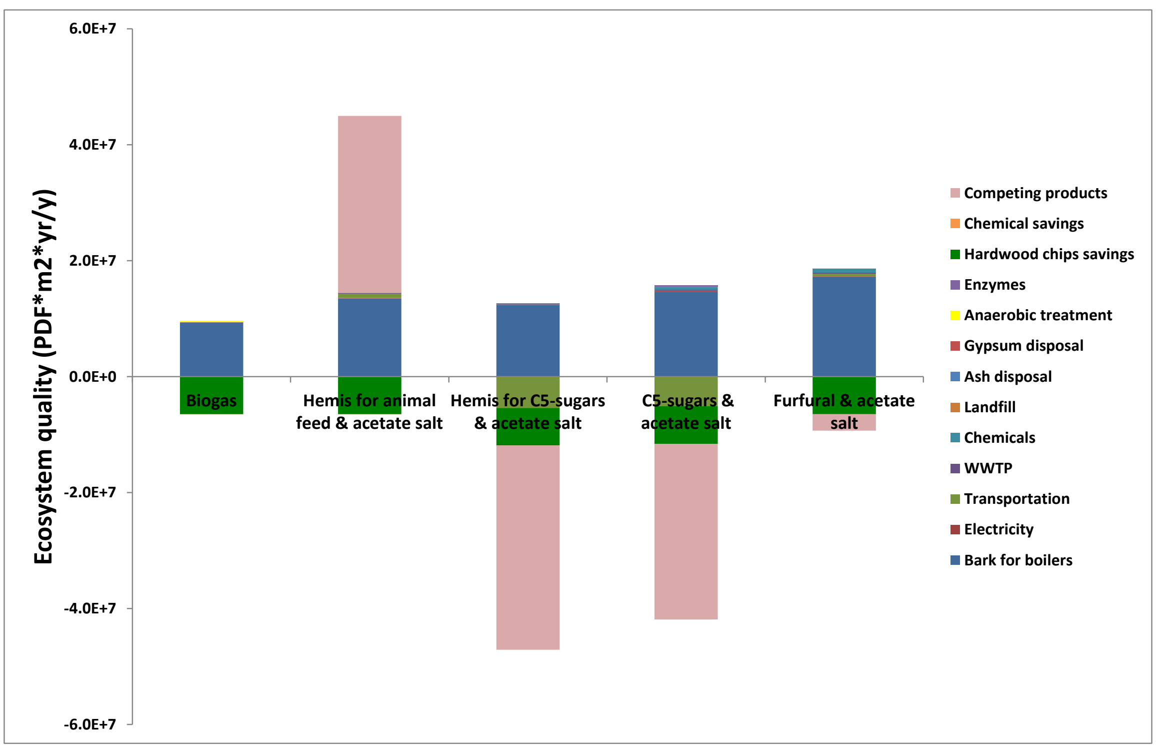

Figure 3-18 Overall ecosystem quality impacts related to HWE-based biorefinery options

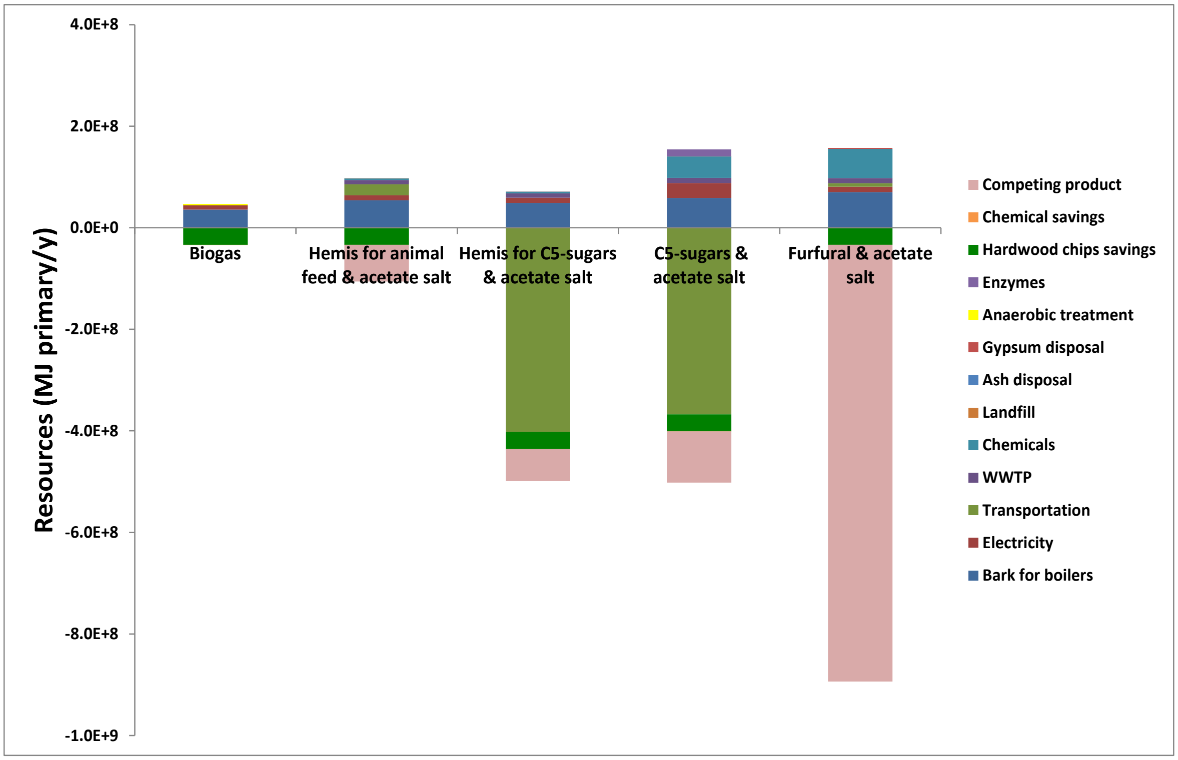

Figure 3-19 Overall resource consumption impacts related to HWE-based biorefinery options

Concerning the overall environmental impacts related to climate change and resources use, negative results for the furfural process option were associated with phenol, as the identified product substitute. In this option, phenol considered to be produced from fossil-based resources. Furthermore, in hemicellulose for C5-sugars and C5-sugars options, the displaced impacts relative to the competing product transportation were significant. Mainly, negative results were due to the avoided impacts relative to the import of sugarcane from Brazil to a sugar refinery in Canada. Negative results associated with sugar production process were mainly due to the consumption of pesticides and chemicals during the life cycle of sugarcane production.

It should be noted that in the case of hemicellulose for animal feed and acetate salt biorefinery, displaced impacts relative to molasses production from sugar beet was identified to be positive. It implied that molasses from sugar beet contributes to environmental credits. Figure 3-20 shows the environmental impacts associated with the production of 1 kg sugar from sugarcane and sugar beet. As can be seen, except for climate change impacts, sugar beet presents more favourable results comparing to sugarcane. This justifies the positive impacts from sugarcane in the animal feed biorefinery option.

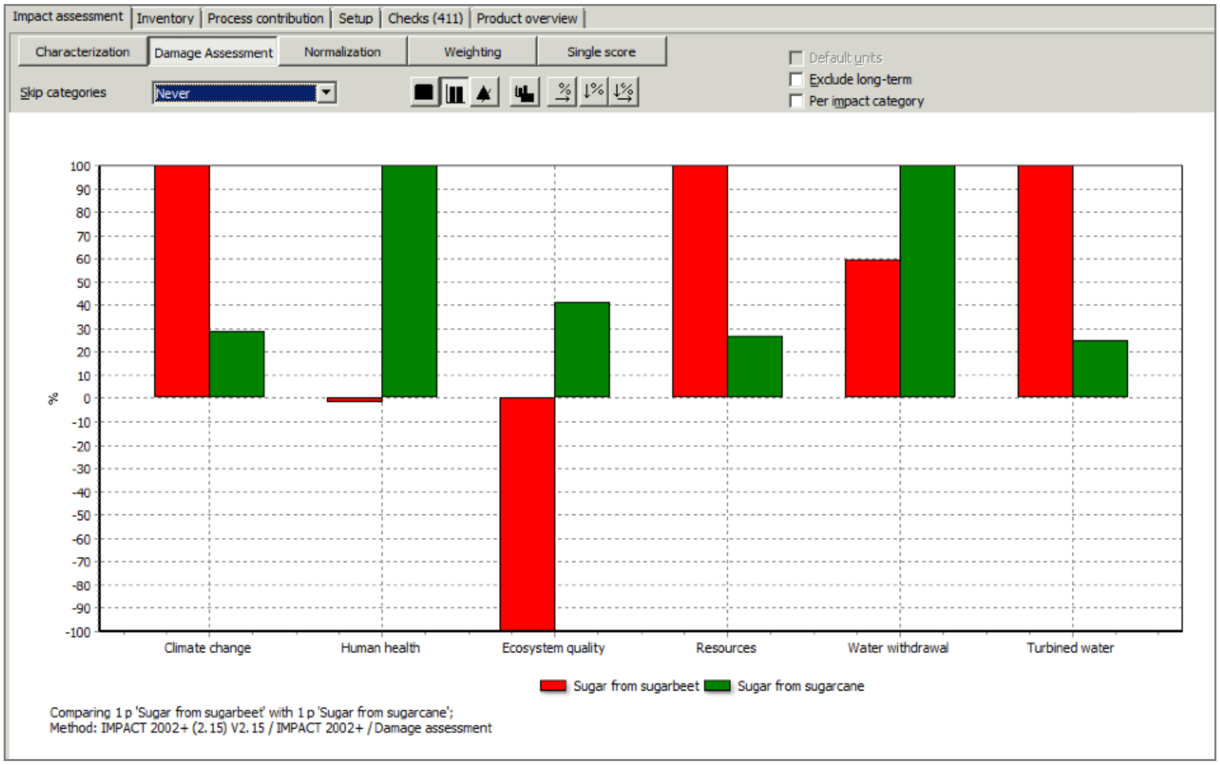

Figure 3-20 Environmental results related to 1 kg of sugar production from sugarcane and sugar beet

3.3.2.3 Net normalized LCA results

Net environmental results were calculated by adding up the positive and negative impacts of all inventory parameters, within a defined impact category. For the purpose of comparing the net results based on a consistent baseline, also providing an overview on the environmental performance related to different HWE-based biorefinery option, net overall results were normalized. Normalization is an appropriate approach to present the net environmental impacts in a comparable manner by using a reference value. There are numerous methods for the calculation of the reference value and in the present analysis; this value was the environmental impact of the existing mill that was considered as the cut-off part. As illustrated in Table 2-5, normalization was based on calculating of the ratio between the net environmental impacts and the impacts related to the board production (cut-off amount). Figure 3-21 depicts the normalized environmental results of the HWE-based biorefinery options. These results served to characterize the environmental benefits and improvements in evaluated impacts.

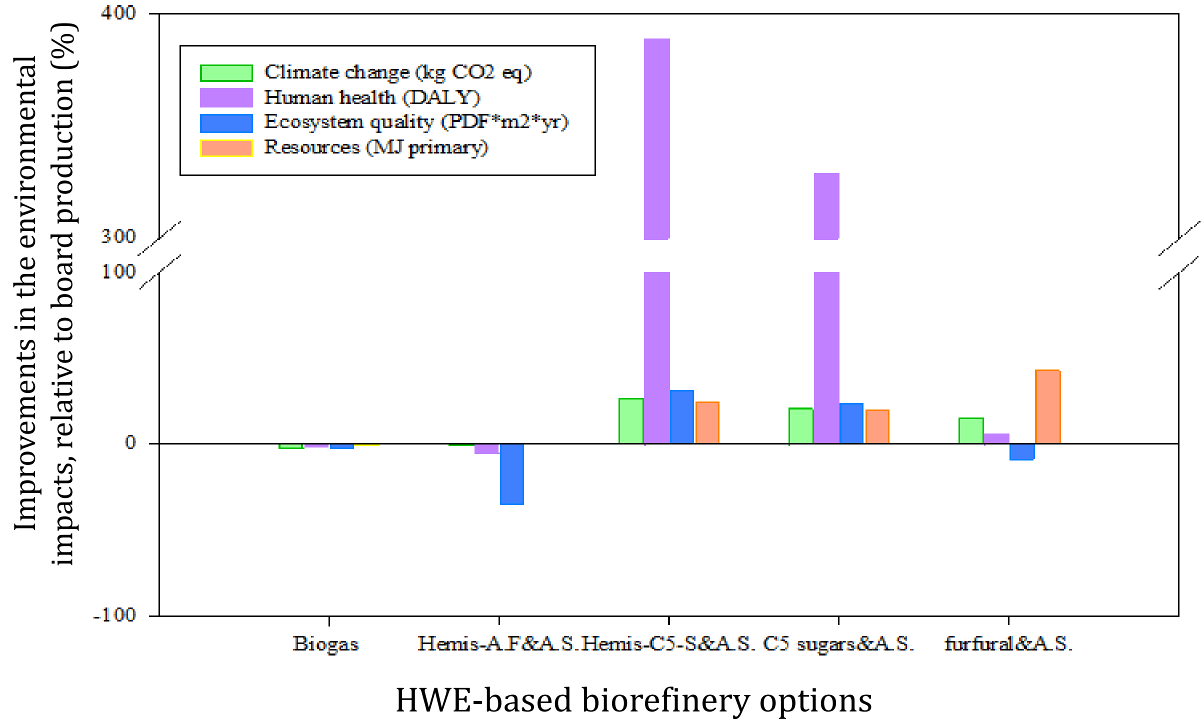

Figure 3-21 Normalized environmental results of HWE-based biorefineries relative to board production

Positive values represent environmnetal improvements relative to the exising mill's performance and negative values show the negative improvement. Based on the net normalized environmental results, hemicellulose for C5-sugars and acetate salt and C5-sugars and acetate salt production processes demonstrated significant environmental performance by having improvements in all the defined impact categories. The climate change impacts were reduced by 26% and 21%, respectively. Moreover, the human health impacts were decreased by more than 3 times, compared with the existing board production process.

Furfural and acetate salt process presented relatively favourable results: climate change improvement by 15% and decrease in resources consumption by 43%. As it was expected, due to internal use of biogas at the existing boilers of the mill and its low production volume, this option did not demonstrate considerable environmental improvements. The worst biorefinery option was identified to be the hemicellulose for animal feed and acetate salt production since all the environmental impact categories, particularly in ecosystem quality, increased.

3.3.2.4 GHG reduction results

One important parameter for the development of biorefinery processes is an improvement in the environmental performance of bioproducts, compared with products that already exist in the market. In particular, reduction of GHG emissions is often a major driver for the sustainability justification of biorefinery projects, and a key parameter that contributes to the success of these projects. GHG emissions represent the carbon footprint of the processes in terms of CO_2 equivalent. For the sustainable strategic biorefineries the reduction of GHG emissions by more than 60% is often sought.

As it was shown in Table 2-5, the reduction of GHG emissions was evaluated considering the net climate change results and impacts from avoided processes and products. Figure 3-22 illustrates the GHG reduction results for the HWE-based production pathways. Biorefinery options related to hemicellulose for C5-sugars and C5-sugars demonstrated considerable environmental results, contributing to 80% and 68% of GHG reduction, respectively. Furfural process option also presented 56% of GHG reduction, relative to the phenol and displaced processes at the mill.

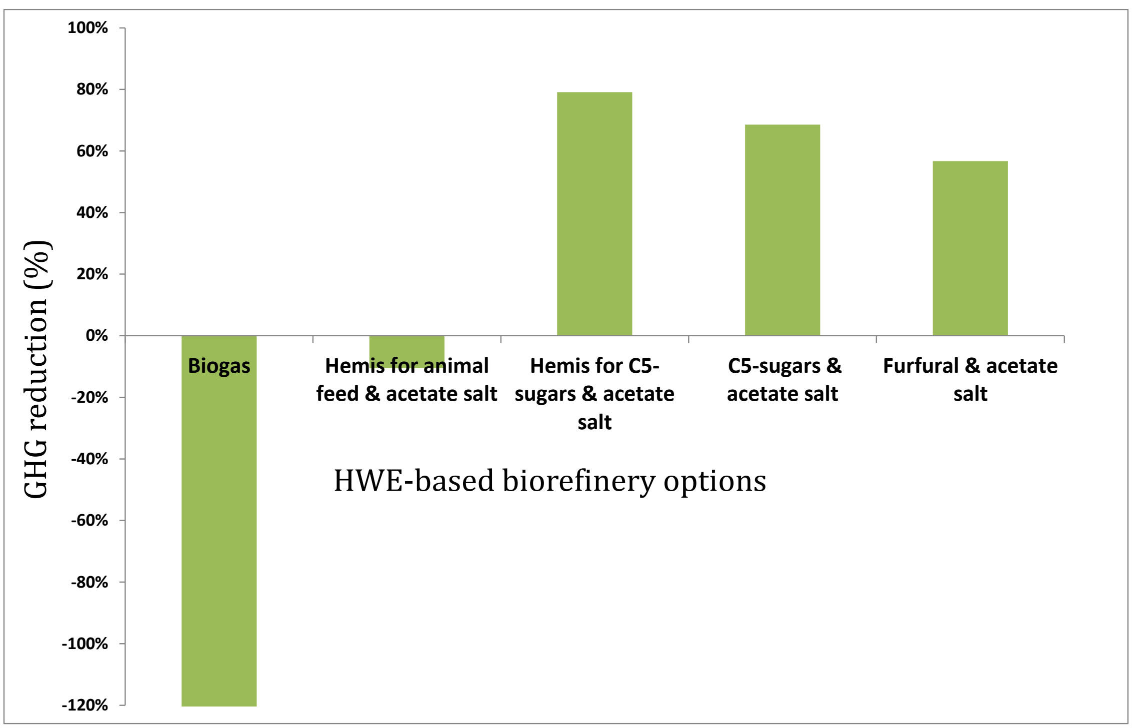

Figure 3-22 GHG reduction results related to HWE-based production pathways

Biogas option resulted in 126% increase in the GHG emissions. As explained above, biogas would be produced and used at the mill site; therefore, the displaced environmental impacts were limited to the avoided wood chips consumption and displaced processes at the mill. These avoided impacts were not significant compared to other biorefinery options. Consequently, the ratio between the net climate change impacts and the displaced products was evaluated to be higher amongst other biorefinery options. Concerning the hemicellulose for animal feed and due to the fact that molasses from sugar beet presented positive environmental impacts, the resulting reduction of GHG emissions was calculated to be 10%, which is not an acceptable value for the purpose of biorefinery implementation.

3.3.2.5 Conclusion

Consequential LCA results for five defined HWE-based biorefinery options were evaluated. Bark, chemicals and product transportation identified to be as main sources of impacts. Hemicellulose for C5-sugars and C5-sugars presented GHG reduction of 80% and 68%, respectively. Also, normalized results of these options proved a considerable improvement of more than three times in the human health impact category, relative to the existing processes at the mill. Biogas option resulted in 126% increase in GHG effects. Also, hemicellulose for animal feed and acetate salt showed an increase in all the environmental impact categories.

3.3.3 Sustainability assessment of HWE-based biorefinery

Identification of the most sustainable strategy plays a significant role in the successful implementation of biorefinery projects. A sustainable biorefinery implementation strategy is the strategy that provides profitability and long-term competitiveness, mitigates market and technology risks in a proper manner and presents remarkable environmental performance.For the sustainability assessment of HWE-based biorefinery options, techno-economic, LCA and risk analyses results were evaluated (Table 3-6).

As explained before, it is well established that to maintain a minimum risk level, a minimum IRR of 20% should be sought. For the purpose of sustaining long-term viability, projects with higher risk such as biorefinery technologies should aim for an IRR of more than 30%. Before the subsidy and except for C5-sugars option with the IRR of 25%, none of the HWE-based options looked economically promising. Nonetheless, according to a preliminary risk assessment, market and technology risks associated with C5-sugars option were identified to be relatively high. By including subsidy, the economic landscape changed drastically and all the defined biorefinery options, excluding biogas, showed considerable project profitability. It was realized that IRR was particularly sensitive to subsidy, especially for hemicellulose for C5-sugars production as a lower capital cost project. Furthermore, it was shown that the two-phase strategy, which aggregated the production of acetate salt and hemicellulose for C5-sugars in phase I and C5-sugars and acetate salt in phase II, had better profitability and risk mitigation performance when compared with single-phase strategies. According to the scenario analysis results, this process option was least affected by the occurrence of all the sensitive parameters and the IRR was only reduced by 11% (difference between basecase and worstcase scenarios). Considering the market and technology risks, it was assumed that the risk levels would improve at least by one level.

Table 3-6 Summary of economic, environmental and risk analysis results

			Biogas	**Hemicellulose for animal feed & A.S.**	**Hemicellulose for C5-sugars & A.S.**	**C5-sugars & A.S.**	**Furfural & A.S.**
Economic parameters	CAPEX (M$)		36.1	25.2	22.4	40.9	35.7
	Annual production cost (M$/y)		-0.5	2.8	2.7	9.2	6.8
	Annual revenue (M$/y)		1.8	5.3	4.6	23.3	14.3
	IRR (%)		3.1	3.9	3.1	25.1	14.4
	IRR (%) (with subsidy)		16.2	44.7	96.4	48	36.6
Environmental parameters	GHG reduction (%)		-126	-10	80	68	56
	Net human health (%)		-1.9	-5.2	389	329	5.8
	Net ecosystem quality (%)		-2.8	-35	31.4	23.8	-8.5
	Net resources (%)		-0.7	0.5	24.9	20.3	42.9
Risk parameters	Technology risk	Main product	Low-Medium	Medium	Low-Medium	Medium	Medium
		By-product		Low-Medium	Low-Medium	Low-Medium	Low-Medium
	Market risk	Main product	Low	Medium	Medium	Medium	Medium
				Medium-	Medium-	Medium-	Medium-

		By-product		High	High	High	High

As previously stated, GHG reduction is regarded as one of the main parameters for promising environmental performance of a biorefinery and GHG results below 60% are considered as the “showstopper”. Hemicellulose for C5-sugars, furfural and C5-sugar options demonstrated significant GHG reduction results. Particularly, both C5-options resulted in the reduction of 80% and 68%, respectively. These HWE-based options presented substantial improvements in all the evaluated impact categories as well.

Due to the consistency between the economic, environmental and risk analysis results, identification of the sustainable process option was relatively straight forward: the aggregated option including the acetate salt and hemicellulose for C5-sugars application in phase I and acetate salt and C5-sugar in phase II was identified to be the most promising and sustainable biorefinery process option.

The analysis presented in this thesis can be used to address the economic, environmental and risks implications of HWE-based biorefinery strategies and for the purpose of early-stage decision-making processes.

CHAPTER 4 GENERAL DISCUSSION

Increase in environmental awareness, concerns regarding the global warming issues and limited fossil-based resources considered as main reasons for the development of biorefinery technologies. Furthermore, forestry companies are dealing with severe financial problems that resulted in losing their competitive positions in the global market. Biorefinery processes are playing an important role in reaching the sustainable development goals by having considerable economic, environmental and social effects that provide promising opportunities in the transition of P&P companies to a more sustainable industry. However, investing in transformation of the forest industry into a biorefinery involves managing several risks including large capital investments, product markets, processing technologies, financial and execution risks. A promising approach is the one that not only takes into account project profitability, but also considers the risk mitigation strategies for the project implementation over both short- and long-term periods.

Regarding the sustainability of biorefinery projects, it is worth mentioning that not all the biorefinery pathways and bioproducts are necessarily sustainable. For instance, environmental footprint of bioproducts depends on the performance and implementation strategy of the biorefinery processes through which they are produced. Identification of the most sustainable strategy plays a significant role in the successful implementation of biorefinery projects. As the biorefinery technologies are continuing to progress, there is a growing demand to have practical-realistic definition and evaluation method of all the parameters that may have potential impacts on the biorefinery accomplishment. A sustainable biorefinery implementation strategy is the strategy that provides profitability and long-term competitiveness, mitigates market and technology risks in a proper manner and presents remarkable environmental performance.

A systematic methodology for evaluating the sustainability of HWE-based biorefinery implementation strategies is proposed. The goal of the study is to illustrate that the development of HWE-based biorefinery process is preferred using a phased-implementation approach to mitigate financial, market and technological risks. Also the sustainability of this can be assessed through the combination of risks analysis and techno-economics and life cycle assessment. The methodology is demonstrated using a case study that involves the integration of HWE pretreatment process into an existing P&P mill. The biorefinery process includes hemicellulose extraction and its further processing for different applications including biogas, hemicellulose for animal feed, hemicellulose for C5-sugars, C5-sugars and furfural. Acetate salt is the by-product of all the process options excluding the biogas.

4.1 Risk mitigation and phased implementation approach

Implementing biorefinery through several phases can reduce the risks associated with immaturity of product market and technologies, and also lack of capital. The level of technology risks related to biorefinery processes will be reduced with time; furthermore, the likelihood of success will increase by starting from simple processes and technologies in phase I and moving toward more complex processes in phase II. For example, in the case of C5-sugars production, advancements in research and process design will continue to improve complex processes like enzymatic hydrolysis and process separation units over time. Market risks will also ameliorate as the bio-economy improves and expands over time.

For strategic biorefinery projects, there should be a profound comprehension of the new and emerging markets and there is an important factor that needs to be considered while implementing a phased approach; it is increasingly critical to be first to the market, due to rapid market changes for specialty chemicals or high value-added products. So if we plan to manufacture these types of products in phase II, a first to the market advantage may be lost and it may be harder to penetrate the market. For instance, acetate salt will be produced mainly in phase I. Due to the small volume of this product and its specialized market, it will benefit from the advantage of being early to the market and having a high market share. However, for primary or intermediate products, there is relatively low advantage for being early to the market and they can be produced in phase II, as well.

Following the identification of feasible HWE-based process-product alternatives, phased approach scenarios are developed to mitigate the financial, market and technology risks. Then, systems engineering tools are employed to assess the economic and risk performance of the developed process options in short-term and long-term. For all scenarios defined in this project, market price volatility (for raw materials and products) and market demand (of products) is expected to vary widely. Particularly for C5-sugars and acetate salt production in phase II, additional risk mitigation strategies are recommended. This strategy involves in a robust business model that allows the complete recycling of these product streams at the mill. Considering the results of risk analysis, it was proved that the two-phase strategy, which aggregated the production of acetate salt and hemicellulose for C5-sugars in phase I and C5-sugars and acetate salt in phase II, had better risk mitigation performance, when compared with single-phase strategies.

4.2 Sustainability assessment

Economic, environmental and risk dimensions need to be evaluated in an integrated sustainability assessment. It is required to design the biorefinery projects with life cycle thinking; in other words having long-term profitability and competitiveness, decreasing life cycle environmental impacts and ensuring long-term market and technology robustness will lead to successful implementation of retrofit biorefineries. A forest biorefinery can be implemented successfully when the available feedstock resources are used efficiently; financing opportunities from different sources are available. Also, there is a need for evolving and optimizing the fractionation technologies along with other sophisticated processes like hydrolysis and fermentation for better integration results. Improvements in the environmental performance of the bioproducts, compared with products that already exist in the market, is regarded as an important parameter for the development of biorefinery projects.

In this project, results of the economic analysis proved that before the inclusion of government subsidy and except for C5-sugars option with the Internal Rate of Return (IRR) of 25%, none of the HWE-based biorefinery options looked economically promising. However, according to the near-term risk analysis, C5-sugar option presented relatively high market and technology risks. After the inclusion of government subsidy, economic profitability of all the defined biorefinery options, excluding biogas, changed significantly. Particularly in low capital cost options such as hemicellulose for C5-suagrs application, IRR was considerably sensitive to subsidy.

Considering the environmental analysis that was performed using consequential LCA methodology, results show that bark, chemicals and product transportation identified to be as main sources of environmental impacts. Biorefinery options including hemicellulose for C5-sugars and C5-sugars presented GHG reduction of 80% and 68%, respectively. Also, these options proved a considerable improvement of more than three times in the human health impact category, relative to the existing processes at the mill.

Since there was consistency between the analysed results, identification of the sustainable process option was quite straight-forward. Considering the results from economic, environmental and risk analysis, the two-phase option including acetate salt and hemicellulose for C5-sugars application in phase I and acetate salt and C5-sugar in phase II was identified to be the most promising and sustainable biorefinery process option.

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Contributions to the body of knowledge

Applying a phase approach to mitigate the market and technology risks

- To account for the financial restrictions and policies in a P&P company, also to mitigate the market and technology risks, a scenario-based phase approach is implemented. Sensitivity and scenario analyses are conducted to bench-mark the process options with single-phase and two-phase investment plans.
- The risk analysis results have potential for being integrated with techno-economic and LCA methodologies for the sustainability evaluation of retrofit HWE-based biorefinery projects.

A systematic methodology for evaluating the sustainability of the HWE-based biorefinery

- A practical and realistic definition of the sustainability in the context of retrofit forest biorefinery projects that include economic profitability, environmental improvement and risk mitigation strategies is defined and the sustainability methodology is validated in a case study.
- This methodology claims to be effective for practical and industrial projects and case studies. Particularly it is applicable in the early-stage decision-making activities in the biorefinery process design.

To sum up, the methodology applied in this thesis exploits sustainability assessment of HWE-based biorefinery processes and starts with the definition of the scope of sustainability. Evaluation metrics in this study include risk mitigation, economic and environmental parameters. To the best of our knowledge, no previous research to date has focused on these problematic in the context of HWE-based biorefinery.

5.2 Future works

5.2.1 Overall methodology

As a future work, the practical methodology proposed in this project can be implemented to address the sustainability of different HWE-based biorefinery processes and production pathways.

5.2.2 Phased approach and risk analysis

The semi-quantitative risk assessment (sensitivity and scenario analysis) performed in this study is based on simple deterministic methods. The conversion factors and levels for qualitative risk parameters are defined subjectively. As potential future work, it is proposed to perform a more detailed risk assessment by defining proper risk criteria. The risk criteria can be calculated and the results can be coupled with techno-economics and environmental analysis in order to identify the most sustainable HWE-based biorefinery process option.

5.2.3 Sustainability evaluation metrics

Regarding the evaluated environmental parameters, life cycle impact assessment performed for the competing products was based on the available proxies in the SimaPro software. As a future work, it is recommended to use primary data for the fossil- or agricultural-based products to evaluate more realistic environmental impacts.

In addition, due to the complexity in the interpretation of the mid-point impact categories, endpoint impact categories were selected as the metrics for the sustainability evaluations. However, endpoint impacts are aggregated results and might not be representative of the real environmental damages. As a future work, it is recommended to perform more elaborations on the definition and interpretation of the mid-point impacts for two major purposes:

- To integrate more reliable environmental results for the sustainability evaluation of HWE-based biorefinery projects.
- To facilitate the interpretation process for decision-making purposes.

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APPENDICES

APPENDIX A – Article 1: Mitigating Risk Through Phased Biorefinery Implementation

Mitigating Risk through Phased Biorefinery Implementation

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Highlights

- Hot water pretreatment results in good recovery of cellulose, hemicellulose and lignin components in a usable form.
- Techno-economic and risk analysis for different process options for retrofitting a hot water extraction biorefinery into a pulp and paper mill were performed.
- Three scenarios including different investment phases for converting hemicellulose to different bio-products were defined.
- According to economic results and risk mitigation approach, process option related to the phased production of C5-sugars and acetate salt was identified to be the most promising alternative.

Keywords

Forest biorefinery, hot water extraction, techno-economic, risk analysis

Abstract

Biorefinery is considered as a promising opportunity for improving the business model of forestry industry. However, retrofitting a biorefinery process into an existing mill introduces significant challenges. A systematic phased approach, taking short- and long-term issues into account, should be used to mitigate the risks associated with biorefinery implementation. Through economic and risk analysis, this study identifies the best phased implementation strategy for retrofitting a hot water extraction biorefinery into an existing pulp and paper mill. Results of economic and qualitative risk analysis show that the two-phase scenario, production of

acetate salt and hemicellulose for C5-sugars in phase I and C5-sugars and acetate salt in phase II, had better profitability and risk mitigation performance, compared with single-phase scenarios. This scenario had an acceptable profitability of 16% and risk mitigation approach. Also, results proved that government subsidies significantly reduce financial risks associated with biorefinery processes, particularly the low capital investment options.

1. Introduction

In recent years, Canadian pulp and paper (P&P) industry has suffered from serious financial difficulties. Integrating forest biorefinery processes into existing mill facilities is considered as an alternative solution for the transformational strategies for the P&P industry.

Significant advancements have been made by a number of researchers who have studied the concepts behind the integration of biorefinery processes. One paradigm receiving attention from the industry is the concept of “Value Prior to Pulping” (ESF-VPP, 2013). VPP is the process of extracting hemicellulose from pulpwood prior to pulping by using hot water and other media, and under different operating conditions (temperature, pressure and residence time). The extracted hemicellulose from wood chips can be used for the production of added-value chemicals and biofuels as well as to improve the yield and quality of pulp. Under certain conditions, the extraction of this component prior to pulping can be done without diminishing the fiber quality (Van Heiningen, 2006). In addition, if the recovery cycle in the pulp mill is a bottleneck, hemicellulose extraction will lead to some offloading in the recovery cycle, which allows mills to increase their pulp production and is economically feasible (Ghezzaz et al., 2012). Hot water extraction (HWE), as a well-proven VPP process, results in good recovery of all of the cellulose, hemicellulose and lignin components in a usable form. With this pretreatment process, the cellulosic component can be efficiently used in the pulp making process, while the extracted stream, which mainly consists of hemicelluloses, can be used as feedstock for various process alternatives (Yoon and Van Heiningen, 2008). HWE is considered as an autohydrolysis process and is conducted under mild acidic conditions that catalyze the hydrolysis of wood constituents. It is an effective method for defibrillating plant cell walls; especially hardwoods and good hemicellulose sugar recovery can be performed after extraction (Amidon et al. 2008).

In a successful application of VPP, American Process Inc. (API) has constructed a commercial biorefinery based on hot water extraction of hardwood chips in Alpena, Michigan. The derivative process from the Alpena project is Green Power+™. In this project, power and bioproduct are co-produced, maximizing the value added products from biomass (API, 2011). The process is cost effective by converting the extracted stream to cellulosic ethanol and potassium acetate. To further demonstrate the versatility of the process, API has considered the production of n-butanol in addition to ethanol as the main product (Cobalt press release, 2011).

However, biorefinery processes are generally capital intensive, requiring significant investments. In addition, they are regarded as high-risk business ventures (HytÖnen and Stuart, 2012). There are different sources of uncertainties in the biorefinery design (Pistikopoulos, 1995):

- Process-inherent uncertainties such as process yield, temperature variations, etc. that are critical especially for emerging, new biorefinery technologies.
- Market volatility: This includes feedstock availability and price; as well as product demand, selling price and quality.
- Process integration uncertainties due to insufficient knowledge at unit operations and business level for scale-up of laboratory or pilot scale processes. Also energy integration uncertainties and risks related to core business.

- Discrete uncertainties such as government policies, technology and product subsidies and available project financing, which are uncertain especially in the context of biorefinery processes.

Prior to considering any biorefinery strategy and making any decision, pulp and paper companies need to be assured that biorefinery implementation has little or no risk for their core business. As for the risks to the mill's core business, it is vital to perform a systematic evaluation on how retrofitting a biorefinery technology might impact the main pulping line, pulp quality and resources utilization (energy system, wastewater treatment and available biomass quantities at the mill).

Although return on investment is an important factor for investors and they look for more profitable alternatives, the risks associated with biorefinery processes are also another critical issue that have to be taken into account by investors. These risks need to be identified and quantified. For this purpose, practical systematic methodologies are required to evaluate and to mitigate the risks associated with the biorefinery. A strategic phased implementation approach is regarded as one of the most important risk mitigation strategies. This incremental implementation of a biorefinery transformation process will minimize the potential risks due to the biorefinery retrofit (Chambost et al. 2008).

In this paper a phased approach for mitigating the risks of a biorefinery retrofit is proposed. To illustrate, a case study mill implementing a HWE-based biorefinery process is used. The objectives of this study are: 1) to identify potential phased implementation scenarios for integrating a HWE-based biorefinery process into a case study mill; 2) to evaluate the techno-economic potentials of the HWE-based process options; 3) to identify and evaluate the market and technology risks associated with HWE-based biorefinery options and to evaluate the best approach considering the return and the risk mitigation.

2. Materials and methods

The implemented methodology for this project started with the identification of potential process-product alternatives, and continued up to the implementation of the different strategies, including the phased approach and performing a qualitative risk assessment with regard to the defined phases. After the definition of investment phases, process block diagrams were developed for each phase and mass and energy balances were performed, based on a "large block analysis" approach with the combined use of apiMAX™ and Microsoft Excel. Large-block analysis (Janssen et al. 2006) was used as a design basis, presenting the potential process systems by a series of large blocks, which were characterized by mass, and energy balances (inputs, models and outputs). As for the risk analysis, a systematic techno-economic analysis was conducted in order to calculate the capital costs, cash flow and the profitability of the process options for different strategies. Following a market review, study context and the identified risks; sensitive parameters that could have an impact on the profitability were defined. Ultimately, a sensitivity analysis was performed to review the impact on project profitability based on variations in external factors and high-risk variables.

2.1. Case study mill and biorefinery process/product options

The case study mill was a Canadian integrated pulp and paper mill, producing 600 bone-dry metric tons (BDt) per day of pulp and from a mixture of hardwoods. In the pulp production process, 65% of the incoming feedstock was from hardwood chips, while the remaining 35% came from recycled fiber. HWE pretreatment considered to be integrated at the mill to extract hemicellulose from wood chips prior to the pulping process. Based on characteristics of the mill and HWE technology, five biorefinery process options were selected for this analysis. Integration of biorefinery in the mill processes in terms of mass and energy, along with a co-location at the existing mill site were considered for each HWE-based production pathway. For all options studied, capacity of the existing pulp production line at the mill was maintained constant and the hemicellulose pre-extraction process was added to the fiber line. The feedstock to the biorefinery was considered to be the mixed hardwoods (maple, birch, and aspen) and hemicellulose extraction was carried out in a HWE digester vessel. Afterwards, the pre-treated pulp would go through the continuous pulp production line.

Figure 1 presents a simplified block diagram, including the major process unit operations for the existing P&P process and the five-biorefinery options. It is worth mentioning that the design of HWE-based biorefinery options in this study was inspired by the biorefinery processes that were developed by American Process Inc. (Restina and Pylkkanen, 2013 and 2014) (Pylkkanen, 2014). The process options were as follows:

A) Extraction of a dilute hemicellulose stream for anaerobic treatment and biogas production

B) Extraction and concentration of hemicellulose (70% dry solid) for animal feed and acetate salt

C) Extraction and concentration of hemicellulose stream (50% dry solid) for C5- sugars and acetate salt

D) Production of C5-sugars and acetate salt

E) Production of furfural and acetate salt

In process option A; anaerobic treatment was performed on the dilute hemicellulose stream. Anaerobic treatment system is designed to remove the organic pollutants that contribute to biological and chemical oxygen demand (BOD and COD respectively) content of the effluent stream, resulting in the production of biogas. Biogas produced was assumed to replace a portion of bark that is currently used for steam production at the case study mill.

An emerging market for hemicellulose is a feedstock to supply producers of bio-fuels, sugars, furfural or other different types of products. The output stream quality (concentration of hemicelluloses, composition and sugar content) must meet the requirements according to the intended application. In process options B and C, the extracted stream was concentrated by a series of re-allocated multi-effect evaporators to different levels. In option B, the sale of concentrated hemicellulose for animal feed production was considered. The molasses product should have at least a 70% sugar concentration in order to meet appropriate calorific content. As for process option C, the extracted stream was concentrated to 50% to be sold to C5-sugar producers. In both options B and C, permeate from the evaporation contained a considerable amount of acetic acid which was removed by filtration. Acetic acid can be used as feedstock to produce different acetate salts like sodium acetate, aluminum acetate, ammonium acetate, potassium acetate and calcium-magnesium acetate. In this study, acetate salt was planned to be mainly used as de-icing agent due to its lower aggressive and corrosive characteristics, compared with existing de-icing substances (Fyvestar, 2014). Further concentration of acetate salt was performed via existing multi-effect evaporation.

In process option D, following the pretreatment and evaporation stages, the concentrated hemicellulose was sent through enzymatic hydrolysis and sugar purification steps. This process yielded C5-sugars as the main product, with low levels of contamination and acetic acid as the co-product. The acetic acid was converted to acetate salt for the production of de-icing material. The majority of C5-sugars are used to produce xylitol, which is a bulk sweetener with recognized unique dental benefits. Other applications of C5-sugars are as an additive in pet food, anti-oxidants for foods as well as pharmaceutical uses (Danisco, 2014).

Process option E included the production of furfural and acetate salt. The pre-extracted hemicellulose stream was concentrated in the multi-effect evaporators, and then it was hydrolyzed by aqueous sulfuric acid in the presence of heat. This process yielded pentose sugars, mainly xylose. Under the same conditions of heat and acidity, xylose was dehydrated to furfural. The product purification step was performed by using liquid-liquid extraction (Marcotullio, 2011). Furfural is a chemical that can be used for the several applications including recovery of lubricants from cracked crude, feedstock for the production of furan resins, also called furfuryl alcohol resins and flavor compound (Ihs, 2014).

2.2. Phased approach implementation

As stated previously, it is evident that a complete transformation of pulp mills into integrated forest biorefineries must be achieved incrementally over the coming years. Using a strategic phased approach that considers both short- and long-term visions is critical for enabling risk mitigation and achieving long-term goals. Chambost et al. (2008) introduced a three-phased approach for the purpose of successful P&P mill transformation into a biorefinery. Phase I and II deal with technological transformation by integration of biorefinery technologies while phase III involves business transformation by modifying the business approach of a company. In this phased approach, the emphasis is on the long-term product portfolio of the biorefinery.

Defining the phases should begin with the design of phase III and based on the results of this phase, the previous phases are designed with the effort to mitigate the risk (Figure 2). Reducing the operating costs is the main objective of phase I. Also, in order to minimize the technology and the market risks, it is recommended to produce bioproducts that can be used internally, or the building blocks that can be sold for production of derivatives. Phase I is regarded as an intermediate step to phase II and at the proper time, phase II investments are made. Phase II represents the long-term vision of the company and intends to create value by the production of high value products. Suitable market analyses in terms of market penetration strategies along with gradual development of the product portfolio are essential parameters to be considered in this phase. In addition, partnership plays an important role to minimize the technical and financial risks (Chambost et al., 2009). In order to have flexibility in strategies, phase II products can be used in more than one application. Phase III aims to maximize the margins and to improve the ultimate results. Manufacturing flexibility, supply-chain re-design and new delivery mechanisms are considered in this phase (Chambost et al., 2008).

In this study, three scenarios were developed using the five above-mentioned biorefinery process options to be implemented in two investment phases. The scenarios are presented in section 3.2 and were defined considering the case study mill, available feedstock, potential markets for the products and the market and technology risks associated with the HWE-based biorefinery options.

3. Results and discussion

The comparison between biorefinery options should include long-term evaluation criteria. This means that the potential production of high value-added products from each option should be considered for the selection of the most promising biorefinery. For biorefinery processes, there is a strong correlation between after-tax internal rate of return (IRR) and plant size; also the process complexity has a direct influence over the initial capital investment. To make a project economically viable, the biorefinery process for smaller sized mills should be simplified in order to facilitate reductions in capital cost. The following sections present the results of the qualitative risk analysis, techno-economic evaluation and sensitivity analysis for the defined HWE-based biorefinery options.

3.1. Preliminary technology and market risk analysis

The qualitative risk analysis performed in the context of this study mainly covers two types of potential risks; market and technology risks for each product stream. Technology risks also include risks that might impact the mill's core business. Considering the risks associated with the biorefinery processes that were already explained, table 1 presents a summary of the near-term market and technology risk analysis performed for each HWE-based biorefinery product. The risk levels were defined as low, low-medium, medium, medium- high and high.

Implementation of an anaerobic treatment on the extracted hemicellulose stream and biogas production presented very low market risk since the product was considered to be consumed internally at the mill. In addition, the technology is well proven; therefore this product option involved minimum technology risk.

Regarding the animal feed option, the market associated with the sell of concentrated hemicellulose as an animal feed additive is fairly a large global market, having high price volatility. Therefore, it is essential to foresee the risks and probable discounts to local consumers in case of developing off-take agreements for this product. The major technical risk for this product was related to its concentration. At 70% concentration, which was essential for this application, the likelihood of having material handling problems, excessive high viscosity and even solidification of the product was high. Moreover, the product concentration stage was assumed to be performed within the mill's existing evaporators. Due to the unique evaporator's configuration and their current capacity also the high concentration level needed in the final output stream, this stage of the process was regarded as a main technology risk that was limiting the solid percentage of the marketable product.

Acetate salt as a deicer presented a high market risk associated with seasonal demand, variability in the required volumes on a yearly basis and the price volatility of the chemicals required for acetate salt production. Technology risk related to this product was low due to the proven production technology. However, in cases that the formate content of the product exceeds the acceptable limit, additional purification systems might be required.

In the product option related to selling of concentrated hemicellulose for C5-suagrs application, the market risks were at a medium level. Risks were mainly related to the agreements with the potential off-take partners regarding the transportation price of the product, as well as the limited market demand. On the other hand, technology risks associated with the evaporation were low to medium, due to the relatively low concentration rate of the product that was required for this option.

In the C5-sugars option, risk analysis results for sugar production illustrated that the market risk was at medium level. There are numerous producers located in Asia who play a large role in the current market (Bin Mohd Noor, 2011). The global market size for C5-sugars is predicted to be 200,000 tons/year. The price volatility is attributed to the periodic overproduction of Chinese producers (Patel et al. 2006). Moreover, the current size of the C5-sugars market in North America is relatively small, with few manufacturing companies. Nonetheless, market growth potential is estimated to increase rapidly due to the growing demand. As for the technology risks associated with C5-sugars production, they were estimated to be medium as well. There were ambiguities regarding the enzymatic hydrolysis, separation and purification steps of the process, especially the presence of formic acid caused by weak acid separation that would threaten the product quality. Also, there is technology risks associated with the process scale-up to large-scale industrial projects (Patel et al. 2006).

Furfural product option presented medium levels of risk for both market and technology. The largest current producers of furfural are located in Dominican Republic and China; with a strong competition coming from Chinese producers (Win, 2005). The global market is estimated to be over 250,000 tons/year and to be growing further to 350,000 tons/year in 2020 (Marcotullio, 2011). However, a growing market in North America, specifically at the pharmaceutical grade, will allow for better market penetration by local producers. The price volatility of furfural is very high due to the variability in Chinese supply. The major technology risk associated with this product is related to the low production yield, also separation and purification steps in the production process (Patel et al. 2006).

In addition to the risks that were identified for each product stream, the major technology risk to the core business was the extraction rate of the hemicellulose; high rates of extraction will result in significant loss in pulp strength and quality.

3.2. Scenarios of phased implementation

Three scenarios that were developed using the defined HWE-based biorefinery process options are illustrated in table 2. As already explained, these scenarios were planned to be implemented in two investment phases. The first scenario uses process option A or B in the first investment phase of the project. The second scenario combines process options C and D into a two-phased investment strategy, where process option C would be implemented in phase I (the first 5 years of production), and subsequently process option D in phase II. Additionally, acetate salt was considered as a co-product in both stages of production. The third scenario refers to the hemicellulose pre-extraction and directly processing the extracted stream for producing the added-value products (C5-sugars or furfural). Knowing that the technology and market risks associated with these products were medium, they considered to be produced in phase II of the project.

Table 2 summarizes the characteristics of the defined scenarios. Generally, the first phase of each biorefinery strategy represents a low-risk, short-term process arrangement in which a commodity product is manufactured. The objective of this phase is risk mitigation and short-term viability. Whereas, phase II involves technology that when implemented, typically results in the manufacture of added-value products and causes higher revenue. However, this phase associates with greater market and technology risks and partnerships are essential to minimize the risks.

It is worth mentioning that the level of technology risks related to biorefinery processes will be reduced with time; furthermore, the likelihood of success will increase by starting from simple processes and technologies in phase I and moving toward more complex processes in phase II. For example, in the case of C5-sugars production, advancements in research and process design will continue to improve complex processes like enzymatic hydrolysis and process separation units over time. Market risks will also ameliorate as the bio-economy improves and expands over time. The key point is to identify potential phase I implementation strategies that are consistent with phase II objectives. In the mean time, exploring alternative scenarios for phase II is necessary, should the market risk for the original strategy not improve over time.

However, there is an important factor that needs to be considered while implementing a phased approach; due to rapid market changes and regarding specialty chemicals or high value-added products, it is increasingly critical to be first to the market. So if we plan to manufacture these types of products in phase II, a first to the market advantage may be lost and it may be harder to penetrate the market. For instance, acetate salt will be produced mainly in phase I. Due to the small volume of this product and its specialized market, it will benefit from the advantage of being early to the market and having a high market share. However, for primary or intermediate products, there is relatively low advantage for being early to the market and they can be produced in phase II, as well.

3.3. Techno-economic analysis

The economic analysis in this work was performed following standard methods, as described by Peters and Timmerhaus (2004). The total capital investment costs were developed for direct and indirect costs. For equipment costs, the first step was to use equipment lists presented in the NREL reports, related to the more mature technologies (Kazi et al. 2010) (Humbird et al. 2011), and filter out only equipment that was similar to those defined in this study. Moreover, the references for capital cost estimates were obtained from vendor quotations for some of the equipment. In order to adjust the equipment size, a scale factor between 0.5 and 0.7 was selected. Subsequently, the equipment costs were indexed with respect to their quotation year, then, they were multiplied by an installation factor. It was assumed that the case study mill had sufficient waste treatment capacity and only minor modifications were required to accommodate the effluent streams from the new processes. Figure 3.A presents the capital cost breakdown for the HWE-based process options of the defined phased scenarios.

Operating costs were developed as the variable and fixed expenditures. Inputs for the operating cost were mass and energy balance results, financial data from the mill and information from the literature. Figure 3.B illustrates the annual production cost breakdown for the HWE-based process options of the defined phased scenarios and shows the positive and negative costs. Negative results represent the cost savings due to modifications in the mill’s existing process, followed by implementation of the HWE-based biorefinery. Particularly, the biogas option presented a significant production cost credit due to the partial bark displacement at the mill’s boilers. In other words, performing anaerobic treatment on the extracted hemicellulose stream and producing biogas contributed to the partial substitution of the bark that was required for the total steam production (total steam needed for the mill and biorefinery processes).

Figure 3.C presents the annual revenue breakdown for the defined HWE-based process options. The product selling price was set according to the market survey and information extracted from the literature. It is worth mentioning that product price for each HWE-based production pathway included the cost related to the transportation of bioproducts from the mill to the potential customer. Considering the current pulping process at the case study mill, no additional wood feedstock was used in the biorefinery process. Woodchip savings were regarded as project revenues, since experimental data showed that at the extraction rate considered as the basis of the present calculations, the overall mill's pulping yield would be improved by the implementation of the HWE-based biorefinery strategy.

A spreadsheet economic model was developed to calculate the cash flow of the biorefinery process options over the next 20 years. The biorefinery plant was assumed to construct over a two-year period. Process options in the phase I scenario were studied as a single investment project over the 20 year period. As well, for phase II process options in the third strategy, a single investment project over the 20 year period was considered. However, the design basis for the options in the second scenario was different. Phase I in this option was assumed to operate for 5 years and the products were sold to external customers during this period. In the third year of phase I production, construction of phase II would start. Afterwards, phase II production commenced and continued for the next 15 years.

Figure 4 illustrates the overall economic performance of the three defined HWE-based phased scenarios and related process options. In this figure, the main economic results including capital investment, annual production cost, annual revenue and internal rate of return is illustrated. Due to having a relatively similar order of magnitude, all of the above-mentioned economic parameters are shown in the same graph.

For the first scenario and regarding the biogas process option, it was assumed that the existing evaporators at the mill would be fully retired and biogas would displace part of the bark consumption in the boilers. However, since the investment cost associated with anaerobic digesters was high and the revenue was only related to the wood chips savings, this option presented the IRR of 3%. Process option related to concentrated hemicellulose for animal feed and acetate salt production did not present good economic results as well and had the IRR of 4%. Poor economic results of the options in this scenario were due to high investment cost and low revenue from the products.

As for the third scenario and the process options that were defined to implement for the phase II of the project, the return on investment was considerably improved due to the production of added-value products. Considering the furfural and acetate salt option, the resulting IRR was shown to be 14%. Alternative process option in this scenario was the production of C5-sugars and acetate salt, directly after the hemicellulose extraction process. Analysis presented good economic results and acceptable profitability and this option contributed to the IRR of 25%, which is a favorable return on investment for the biorefinery projects. However, as mentioned earlier the market and technology risks associated with this alternative are high. In order to mitigate these risks and having the acceptable profitability, the second scenario was defined for the production of C5-sugars and acetate salt.

Three options were defined for the second scenario to illustrate the impact and benefits of phased implementation approach. In the first option, due to the relatively high investment cost and low product revenue, phase I resulted in a low IRR of 3%. For the second option, the incrementally favorable economic results of phase II provided an IRR of 42%, which is the highest return among all the process options. For this option, the analysis was based on the economic assessment of incremental costs and revenues associated with the production of C5-suagrs and acetate salt for 20 years and costs of hemicellulose production in the previous phase were excluded from the economic assessment. The third option refers to the production of C5-sugars and acetate salt in two project phases. The design basis for this option was to produce hemicellulose for sale in phase I (for 5 years) and to vertically integrate C5-sugars production for 15 years in phase II (aggregated phase I and phase II). The economic results of this option were acceptable and the overall project IRR was 16%. In this particular option, it is expected that by the implementation of a phased approach, the technology and market risks associated with biorefinery integration will be significantly reduced.

In general for successful strategic projects, a minimum IRR of 20% should be sought to maintain the minimum risks. However, projects with higher risk such as biorefinery technologies should aim for an IRR of more than 30%. Figure 5 presents the IRR results of all scenarios, with and without the inclusion of the government subsidy. A fixed subsidy of 15 million Canadian dollars, to be obtained from the Investments in Forest Industry Transformation (IFIT) program of Government of Canada, was considered for the biorefinery process options.

It was realized that IRR was particularly sensitive to subsidy, especially for lower capital cost projects. This in turn, implied subsidy’s role to mitigate the financial risks associated with the biorefinery technologies. Especially in case of hemicellulose for C5-sugars and acetate salt production in phase I of the second scenario, IRR was found to change considerably from 3% to 96%. Also, the aggregated option (phase I and phase II) presented interesting economic results after the inclusion of subsidy and the IRR was changed from 16% to 41%. However, this subsidy would be granted only for the first year of the project and particularly would not be applicable for phase II of the second scenario.

3.4. Sensitivity Analysis

As a method for risk quantification, sensitivity analysis was performed to examine the impact on project profitability due to variations in external factors. Although any number of metrics could be employed to describe the potential of a capital-spending project, the internal rate of return was selected as the basis for the sensitivity analysis of the HWE-based biorefinery project. Following preliminary identification of the technology and market risks associated with the HWE-based process options, which were previously explained in section 3.1, the major sensitive parameters with potential impact on the IRR were identified. Table 3 shows the identified sensitive parameters for the biorefinery process options, including their justification. In the context of this analysis, three parameters were chosen: capital cost (CAPEX), operating cost (OPEX) and revenue. Figure 6 illustrates the results of the sensitivity analysis for the biorefinery options that were defined for the second scenario.

In regards to the first process option of the second scenario, i.e. concentrated hemicellulose for C5-sugars and acetate salt (Figure 6.A); profitability of the project was greatly sensitive to increased CAPEX if acetate salt purification was required, and under-estimated CAPEX for the HWE digester. However risks associated with the former parameter were believed to be low. Also in the case with financial subsidies, the impacts of these two parameters and their variations were considerable. Moreover, increase in the price of chemicals (hydroxide) that was used in acetate salt production (OPEX parameter) and a decrease in wood chips price (revenue item due to pulping yield improvement) had negative impacts on internal rate of return. Results of the analysis proved that the project profitability was highly dependent on the negotiated selling price of the concentrated hemicellulose and acetate salt. It should be noted that downside and normal IRR must be around the preferred acceptable range, which was defined to be 25% in this study. In case of this process option, the normal, downside and even upside IRR were lower than minimum acceptable range (11%). However, with inclusion of the government subsidy, it was proved that project profitability could reach higher than the preferred acceptable level.

Figure 6.B presents the sensitivity analysis results for the second process option of the second scenario (incremental production of C5-sugars and acetate salt). IRR was sensitive to the decrease in C5-sugars production yield. C5-sugars process was regarded to be complex, due to complicated separation and purification units; also the enzymatic hydrolysis step had a significant impact on the process yield. In addition, IRR was sensitive to underestimated CAPEX for C5-sugars production and increase in C5-sugars production cost. Project profitability was considerably dependent on the negotiated selling price of C5-sugars and results proved that IRR could become interesting for increased product selling price.

Considering the third process option (acetate salt and hemicellulose for C5-sugars in phase I and acetate salt and C5-sugars in phase II) and according to the results presented in figure 6.C, the profitability of the project was highly dependent on the revenue from the product streams in each phase. This in turn, implied the role of having negotiations over the product selling price also concrete off-take agreements prior to implementation of a biorefinery project. According to the presented results, IRR was negatively affected by the decrease in C5-sugars production yield. Moreover, under-estimated CAPEX for C5-sugars and increase in its production cost played a great role in profitability decrease.

4. Conclusion

Investing in transformation of the forest industry into a biorefinery involves managing several risks. Techno-economic and qualitative risk analyses for retrofitting a HWE-based biorefinery into a case study mill were performed. Results proved that the most recommendable option was the production of acetate salt and hemicellulose for C5-sugars in phase I and C5-sugars and acetate salt in phase II. In this option, the overall IRR was acceptable (16%) and due to implementation of phased approach, it was the best choice in terms of risk mitigation over time. Furthermore, government subsidies significantly decrease the financial risks associated with biorefinery process options.

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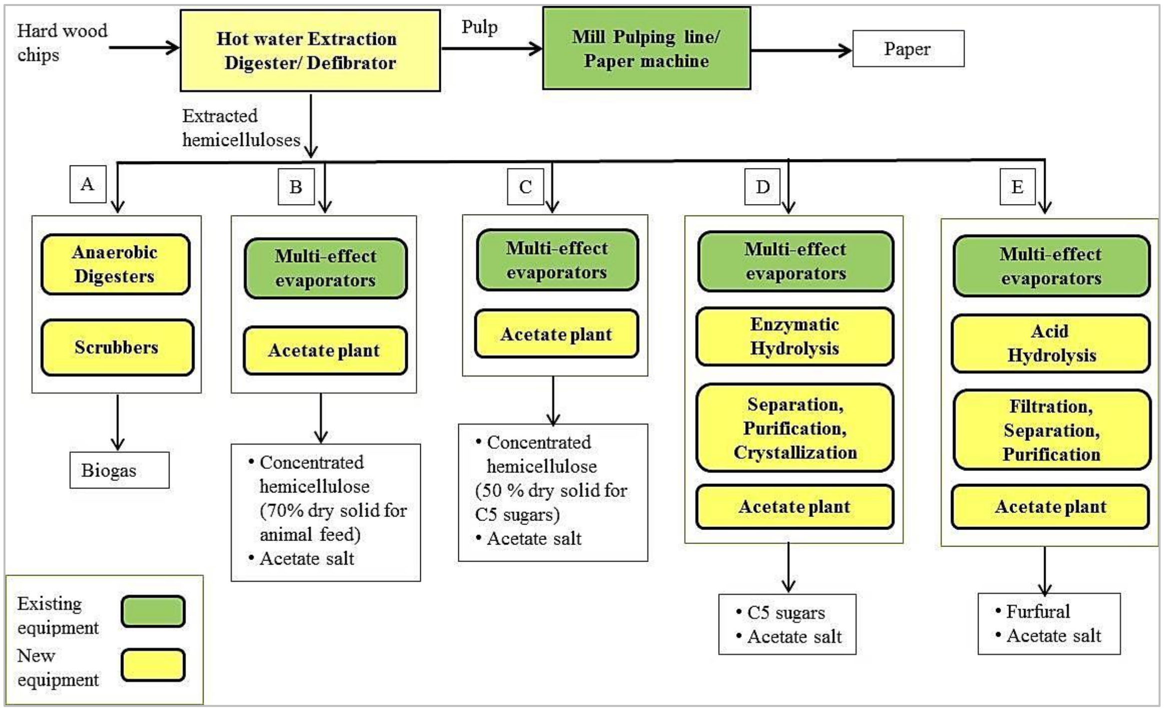
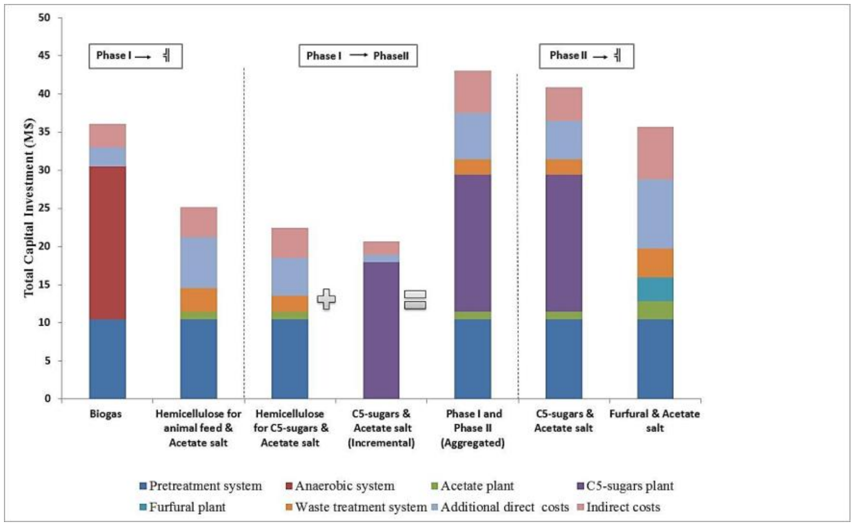


Figure 1 - Simplified block flow diagram for HWE-based biorefinery process options

Figure 2 - Strategic phased implementation of the forest biorefinery (Chambost et al. 2008)



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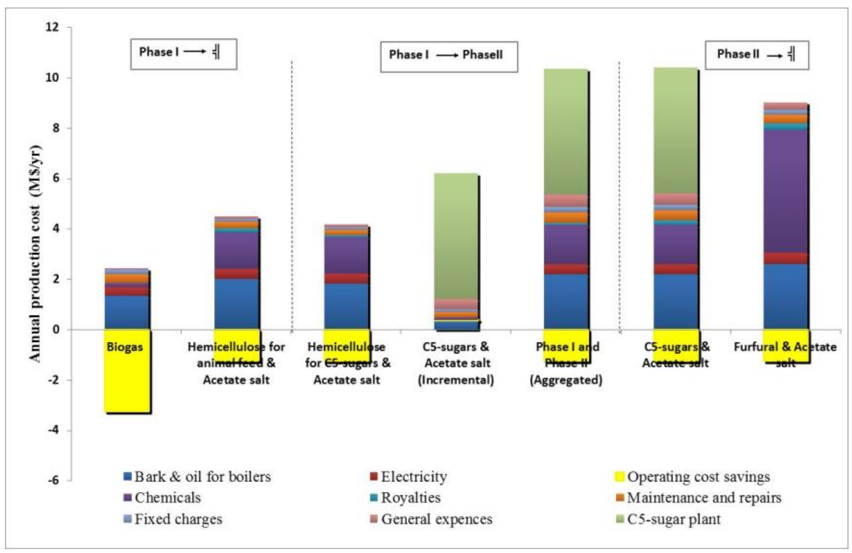

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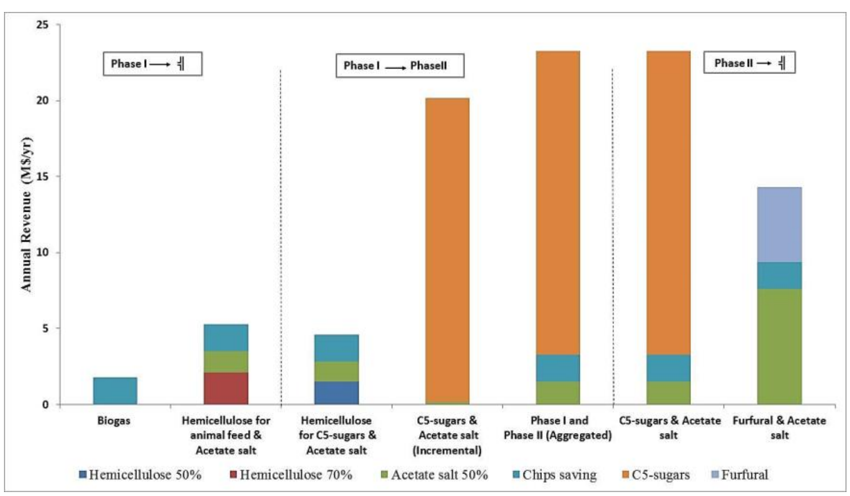

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Figure 3 – Breakdown of evaluated economic parameters for HWE-based process options A) Total capital investment B) Annual production cost C) Annual product revenue

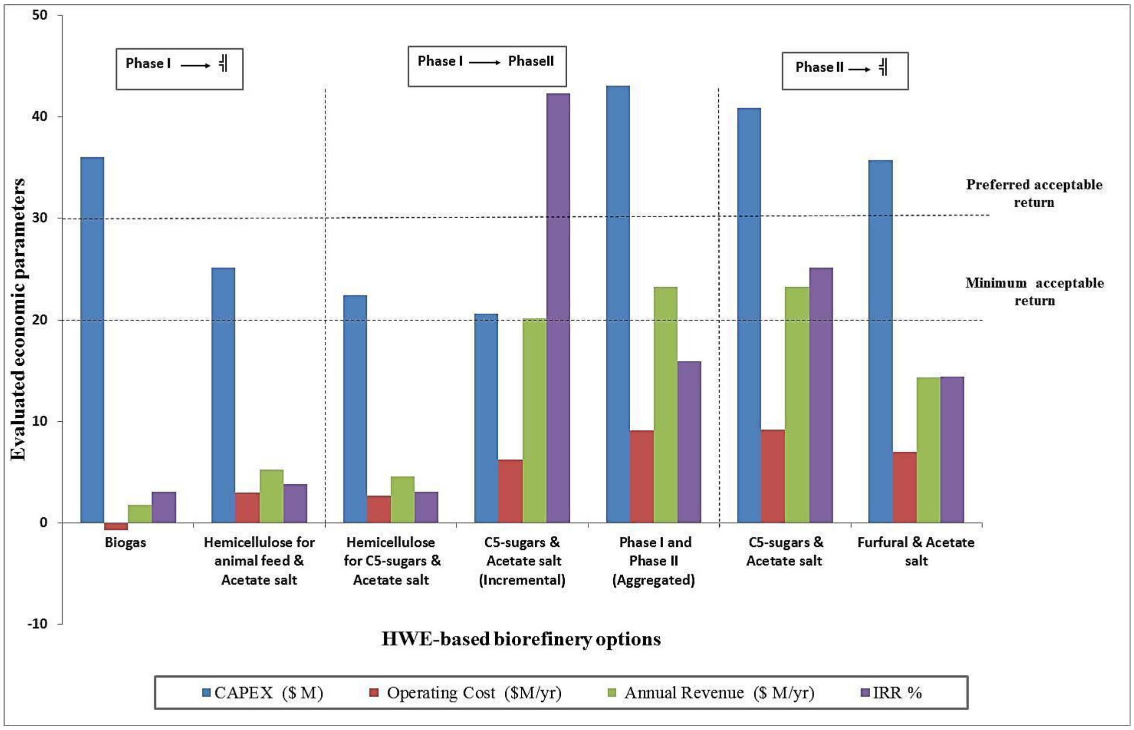


Figure 4 - Overall economic performance of HWE-based process options and phased scenarios

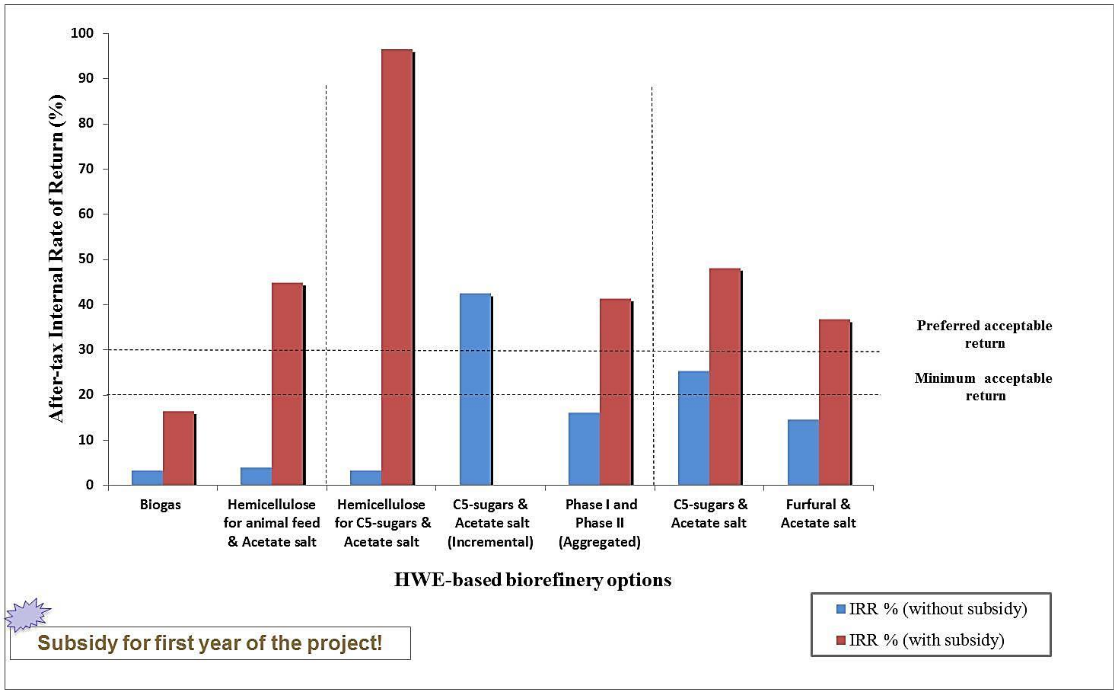
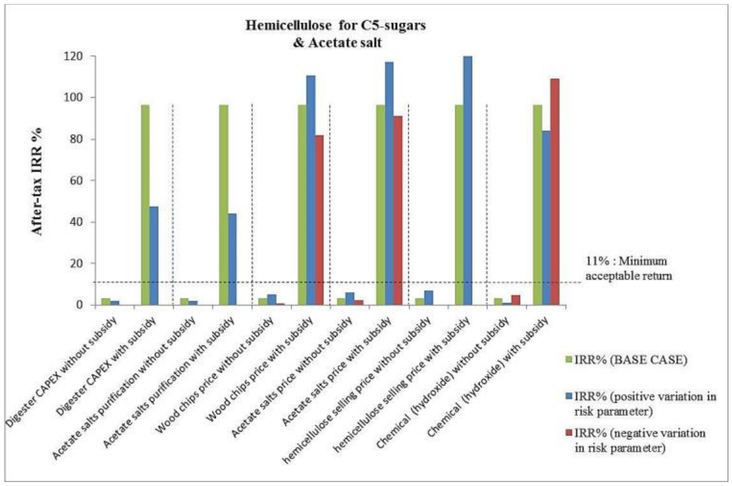


Figure 5 – After-tax internal rate of return for the HWE-based process options, with and without Government subsidy



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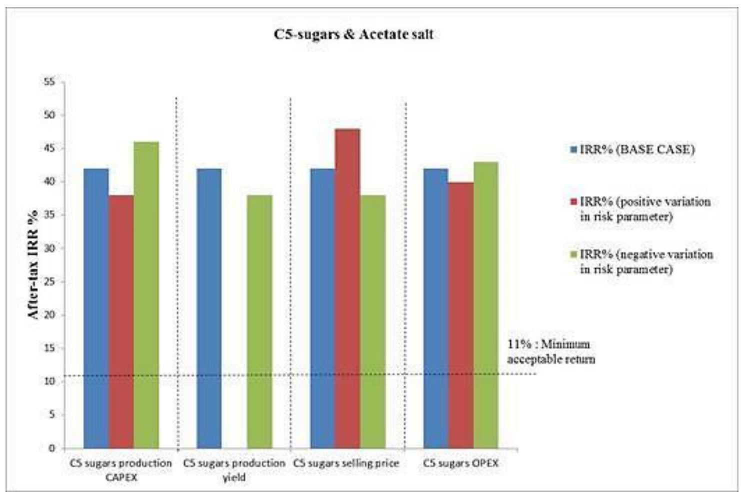

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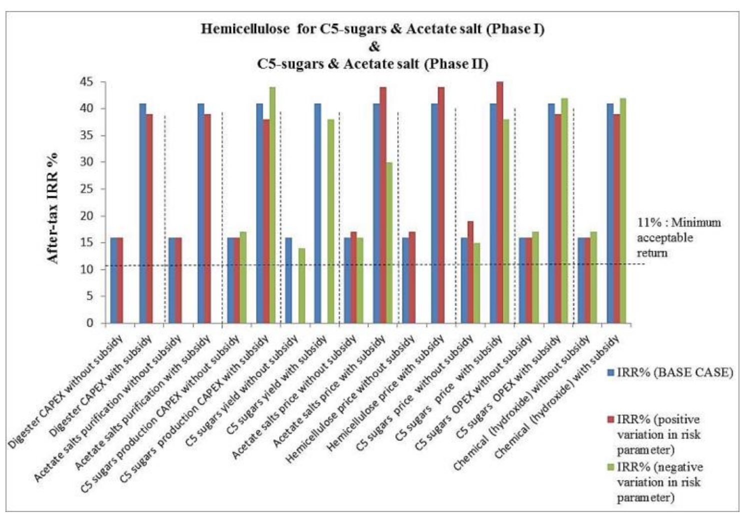

C.

Figure 6 - Sensitivity analysis results for biorefinery process options in the second scenario A) hemicellulose for C5-sugars and & acetate salt B) C5-sugars and acetate salt C) hemicellulose for C5-sugars and & acetate salt in Phase I and C5-sugars and acetate salt in Phase II (Aggregated)

Product	Market risks	Justification	Technology risks	Justification
Biogas	Low	Biogas would replace a portion of bark currently used in the mill boilers	Low-Medium	1.Well-proven technology 2.limited experience with hemicellulose
Concentrated hemicellulose (70% dry solid for animal feed)	Medium	1.Selling price is dependent on product concentration 2. Many sellers in the market 3. High price volatility	Medium	Reallocation of unique configuration evaporators: 1. Available evaporator capacity. 2. Liquor viscosity at high concentration
Acetate Salt (as de-icer)	Medium -High	1. Price depends on seasonal demand, winter severity. 2. Product compostion; i.e. Formate content	Low-Medium	1.Proven technology-API demonstration plant in Alpena-Michigan 2. Purification of the product might be required.
Concentrated hemicellulose (50% dry solid for C5-sugars)	Medium	1. Transportation cost is dependent on product concentration. 2.Limited market volume with few manufacturing companies.	Low-Medium	1. Required product concentration is achievable by using existing evaporators, minimum risk for evaporators.
C5-sugars	Medium	1.Strong competition with China (supply & demand volatility) 2.Growing demand in N.A 3.Limited market volume with few manufacturing companies.	Medium	1. Complicated process (Enzymatic hydrolysis) and complicated separation and purification units.
Furfural	Medium	1.Early in N.A. market & growing demand in N.A. 2. Strong competition with China	Medium	1. Due to complex separation process.

Table 1 - Near-term market and technology risk analysis for the HWE-based Biorefinery products

Scenario	Scenario implementation → Time	Biorefinery options	Targeted attributes to keep option for further analysis
1. Commodity products	Phase I →	3. Biogas 4. Concentrated hemicellulose for Animal feed & Acetate salt	Large volume / limited margins / Lower market & technology risks / subsidies are possible in near term
2. Commodity to added-value products	Phase I → Phase II	• Concentrated hemicellulose for C5-sugars & Acetate salt → C5- sugars & Acetate salt	Stage wise development/ lower market & technology risks/ small but growing product demand for phase II product/ Partnership (Joint Venture) is recommended for phase II
3. Added-value products	Phase II →	• C5-sugars & Acetate salt • Furfural & Acetate salt	Early to market/ higher market and technology risks/ market for phased II product must be available in the near term/ Partnership (Joint Venture) is recommended

Table 2 – HWE-based biorefinery phased scenarios

Category	Sensitive parameters	Justification
HWE Digester	Digester CAPEX	Possibility of capital cost increase due to unforeseen scope changes and limitations in available space at the mill.
Acetate salts	Acetate salts purification CAPEX and OPEX	Purification system (extractive distillation) for removing the formate in the product
C5 sugars	C5 sugars production CAPEX	Possibility of capital cost changes due to unforeseen scope changes and complexity of the process
	C5 sugars production yield	Possibility of decrease in process yield due to complicated process units (enzymatic hydrolysis, separation and purification units)
Anaerobic treatment	Anaerobic treatment CAPEX	Possibility of capital cost changes due to complexity of the process
Furfural purification	Furfural purification CAPEX	Possibility of capital cost changes due to complexity of the process(purification system consisting of strippers, Decanters, Dehydrator and low boiling point column)
OPEX	Biomass for boilers	Price volatility and trend for required bark for boilers
	Sulphuric acid price	Price volatility for chemicals (required acids for hydrolysis)
	Chemical (hydroxide)	Price volatility for chemicals (hydroxide)
	C5 sugars OPEX	Many external factors (enzyme, fuel price,etc.) may change the operating cost.
Revenue	Wood chips Biomass savings	Price volatility and trend for feedstock wood chips
	Acetate salts price	Price depends on seasonal demand, winter severity and product composition.
	hemicellulose selling price	Price depends on product concentration and market negotiations
	C5 sugars price	Growing demand in N.A. and supply and demand volatility
	Furfural selling price	Range of furfural selling price for industrial and pharmaceutical applications

Table 3 - Sensitive parameters and justification

APPENDIX B – Article 2: Life Cycle Assessment of an Integrated Forest Biorefinery: Hot Water Extraction Process Case Study

Life Cycle Assessment of an Integrated Forest Biorefinery: Hot Water Extraction Process Case Study

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Keywords

Forest biorefinery, hot water extraction, Life cycle assessment, sustainability analysis, consequential LCA

1. ABSTRACT

The environmental footprint of bioproducts depends on the performance and implementation strategy of the biorefinery processes through which they are produced. Consequential Life Cycle Assessment (LCA) is known to be the proper approach to address the environmental analysis of integrated biorefineries with multiple bioproducts.

In this study, LCA of hot water extraction-based biorefinery strategy, including five production pathways was conducted. The defined process options consisted of extraction of hemicellulose to produce biogas, hemicellulose for animal feed, hemicellulose for C5-sugars, C5-sugars and furfural. Except for biogas, acetate salt was the by-product of all the process options.

Consequential LCA results proved that bark consumption, chemicals and bioproduct transportation have significant impacts. Hemicellulose for C5-sugars and C5-sugars outperformed other alternative process options, having GHG reduction of 80% and 68%, respectively. Also, normalized results of these two options presented remarkable improvement of more than three times in the human health impact relative to existing process at the case study mill.

2. INTRODUCTION

Biorefinery processes, having substantial economic, environmental and social effects, provide promising opportunities for forestry companies.[1] Integrated biorefinery is a processing facility for the biomass transformation into value-added products. In biorefinery, all types of biomass feedstocks can be converted to various types of biofuels and biochemicals through different technology platforms. The main objective of implementing a biorefinery project is to develop sustainable sources of renewable energy and products that can displace fossil fuels and fossil-based products, increase energy security, promote environmental benefits and create economic opportunities. This offers opportunities for forestry companies to be more competitive and to progressively replace fossil-based products. [2]

Numerous studies have been done in recent years for the sustainability evaluation of biorefinery technologies. However, moving towards sustainability requires reconsidering of the design of production systems, product consumption and waste management.[3] Therefore, economic and environmental evaluation of different biorefinery implementation options is of great importance for the optimum use of resources and reducing the related environmental impacts.

Economic sustainability of a biorefinery project can be ensured through monitoring and forecasting the investment costs, profitability, productivity and efficiency across the entire supply chain and for multiple feedstocks and production pathways.[4] Environmental sustainability implies a commitment to continuous improvement in the environmental performance. Biorefinery offers significant potential to mitigate climate change by reducing lifecycle GHG emissions, relative to competitive fossil-based products. Although producing biomass-based products releases carbon dioxide, biomass absorbs carbon dioxide from the atmosphere as it grows. On the contrary, fossil-based products release carbon that has been sequestered for a long period of time, resulting in a net positive increase in the atmospheric carbon. [5]

Various approaches have been developed to perform the environmental evaluation of the biorefinery processes: Environmental Impact Assessment (EIA), Regulatory requirements for the estimation of the process emissions, Best Available Technology (BAT) Analysis [6] and Life Cycle Assessment (LCA). LCA is considered as a promising tool in assessing the environmental sustainability of technological options due to its capability to evaluate the potential effects in the ecosystem, also on population and human health that might endanger the current and future generations.[7] The holistic environmental approach that LCA provides on products has made it valuable for environmental management in industry and environmental policy-making in government.[8] For the biorefinery projects, LCA that uses a whole life cycle perspective is preferable and can be used to evaluate replacing fossil-based products and fuels by bioproducts. By considering impacts throughout the product life cycle, LCA provides a comprehensive view of the environmental trade-offs for different biorefinery processes. Moreover, by interpreting the results of the evaluations, LCA can be employed to help decision-makers with making more informed decisions. [9]

Several authors have explored implementation of the LCA methodology in environmental assessment of the biorefinery projects. Mu et al.[10] compared the environmental performance of the two primary lignocellulosic ethanol production pathways, including biochemical and thermochemical conversions. Contreras et al.[11] performed LCA on the by-products of sugar cane production. They defined four alternative product implementation strategies, using the by-product stream of the sugar production process. They analyzed the environmental impacts of the defined options and based on their results, the major impacts common between all the four alternatives were the land use change and respiratory inorganics. Neupane et al.[12] completed an in-depth analysis of GHG emissions and resource consumption across the whole supply chain of wood-derived bioethanol, using the near-neutral hemicellulose extraction technology. The focus of their study was on the assessment of energy consumption and they found that lignocellulosic ethanol production under the near-neutral pretreatment condition demonstrated higher environmental performance, when compared with fossil-based fuels or even corn ethanol. Lim and Lee[13] implemented the consequential LCA approach to analyze the environmental consequences of the production of second-generation biofuels, bioethanol from palm oil biomass, compared to existing palm oil bio-diesel production.

The detailed LCA approach has been extensively-applied by the systems analysis research team at École Polytechnique de Montreal (Canada), including specifically for evaluation of biorefinery process-product options. Gaudreault et al.[14,15] reviewed the life cycle application in the pulp and paper industry and identified opportunities for improvement of LCA methodologies, using consequential analysis. They compared the information provided by attributional and consequential LCA approaches for decision-making in order to select the best process option, which leaded to less dependence of the mill to purchased electricity. Liard [16] studied the environmental assessment of a Triticale-based biorefinery using LCA. She carried out Multi-Criteria Decision-Making (MCDM) studies to identify the most representative, comprehensive and interpretable environmental criteria, along with technical, economic and commercial criteria. More recently, Batsy [17](Batsy D, unpublished) performed the environmental impact assessment of forest biorefinery product portfolio using a comprehensive LCA analysis. He implemented the consequential LCA and cut-off procedure in his LCA methodology. Furthermore, he conducted an MCDM-based assessment identifying a set of practical and interpretable environmental criteria for evaluating a series of biorefinery strategies for a forestry company.

As one of the well-proven biorefinery technologies, hot water extraction (HWE) refers to the process of hemicellulose extraction prior to pulping process. This pretreatment is the first process step to extract value from woody biomass without significantly affecting the solid material or the remaining pulp. The fractionation process results in the removal of extractives and hemicellulose from wood, while cellulose and lignin largely remain in the residual pulp structure.[18]

HWE-based biorefinery is considered a promising process for converting pulp mills into biorefineries. However, in the context of sustainability and process implementation strategies, it is critical to evaluate the environmental performance of the bioproducts that can be manufactured from the HWE process. In this study potential environmental consequences and incremental impacts of five production pathways, which were defined for the integrated HWE-based biorefinery process, were evaluated. Following the methodology of consequential LCA, environmental impacts through the life cycle was assessed using a “cradle-to-gate” perspective. Four end-point impact categories were calculated including climate change, human health, ecosystem quality and resources.

The goal of this LCA study was to analyze the environmental performance of different HWE-based biorefinery production pathways on a transparent and comprehensive basis in order to compare; (A) the environmental results of HWE-based biorefinery options, using the consequential impact perspective, and (B) to analyze the net environmental benefits relative to the impacts from the paper production in order to provide a perspective on the importance of changes in the environmental performance due to the implementation of different HWE-based biorefinery options. The scope of this study was Cradle to Gate; potential environmental impacts were evaluated from the feedstock growing and harvesting until delivery of bioproducts to the gate. Gate was considered as the targeted customer's gate for the defined biorefinery options.

3. MATERIAL AND METHODS

LCA was used as an analytical tool and environmental analysis was performed following the standard practices that were defined by the ISO 14040 series.[19-22] In addition, modelling of processes and impact assessment were carried out using SimaPro 8.0 Multiuser LCA software and IMPACT 2002^{+} (version 2.15), respectively.[23] Regarding the Life Cycle Inventory (LCI) database, Ecoinvent AmN CIRAIG was employed. This database is developed by Interuniversity Research Centre for the Life Cycle of Products, Processes and Services (CIRAIG), to adapt the international ecoinvent database to the Quebec and Canadian contexts.

Sources of data for the life cycle inventory included mass and energy balances of the existing mill, publically available data from the literature review and data from technology providers. In addition, North American data that was available in SimaPro software was applied in cases of primary data limitation and scarcity of information; particularly for chemicals that were used in the HWE-based biorefinery processes, and also for bioproducts substitutes. For the steps regarding the procurement of forestry feedstock, bark, chemicals, electricity and other required input material to the mill, available data from mill was used.

3.1 Case study mill and HWE-based biorefinery options

The case study mill was a Canadian integrated pulp and paper mill, producing 600 bone-dry metric tons (BDt) per day of pulp and from a mixture of hardwoods. HWE pretreatment considered to be integrated at the mill to extract hemicellulose from wood chips prior to the pulping process. Based on characteristics of the mill and HWE technology, five biorefinery process options were selected for this analysis. It is worth mentioning that the design of HWE-based biorefinery options in this study was inspired by the biorefinery processes that were developed by American Process Inc. [24,25,26]

Figure 1 presents a simplified block flow diagram, which includes the major process unit operations for the existing P&P process and the biorefinery options. Integration of biorefinery in the mill processes in terms of mass and energy, along with a co-location at the existing mill site were considered for each following HWE-based production pathway:

A) Extraction of a dilute hemicellulose (Hemis) stream for anaerobic treatment and biogas production: this treatment system was designed to remove the organic pollutants that contribute to biological and chemical oxygen demand (BOD and COD) content of the effluent stream. In this design analysis, produced biogas was assumed to have internal application, in order to replace portion of the bark for steam production in the biomass boilers of the case study mill.

B) Extraction and concentration of hemicellulose (70% dry solid) for animal feed and acetate salt: the extracted stream was concentrated by a series of existing, re-allocated multi-effect evaporators to 70% dry solid. The molasses product with this concentration and certain calorific content was suitable for animal feed production. Permeate from the evaporation contained a considerable amount of acetic acid, which was removed by filtration, concentered via multi-effect evaporation and converted to acetate salt (A.S.).

C) Extraction and concentration of hemicellulose stream (50% dry solid) for C5- sugars and acetate salt: In this option, the extracted stream was concentrated by a series of existing multi-effect evaporators to 50% dry solid in order to be sold to C5-sugars producers. Same as option B, acetate salt was the co-product of the evaporation stage.

D) Production of C5-sugars by enzymatic hydrolysis and acetate salt: following the pre-treatment and evaporation stages, the concentrated extracted hemicellulose was sent through enzymatic hydrolysis and sugar purification steps, resulting in C5-sugars with low levels of contamination. In addition, acetate salt was also produced as a co-product in this option.

E) Production of furfural by dilute acid hydrolysis and acetate salt: the pre-extracted hemicellulose stream was concentrated in the existing multi-effect evaporators, and then it was hydrolyzed by dilute sulfuric acid in the presence of heat. The produced xylose from hydrolysis stage was dehydrated to furfural and the product purification was performed, using liquid-liquid extraction. The acetate salt was considered to be the by-product of the process option.

Modelling of HWE-based biorefinery options was performed based on very detailed and accurate information reflecting relatively true production conditions. Using the primary data from literature review and the technology providers, process block diagrams were developed for each biorefinery process option and mass and energy balances were performed, based on a "large block analysis" [27] approach with the combined use of apiMAX™ simulation software and Microsoft Excel.

3.2 System boundary and functional unit

In recent years, consequential LCA methodology along with system expansion is frequently applied to analyze the environmental performance of integrated biorefinery processes. Consequential LCA is an approach that is mainly used to describe the consequences of a decision, for the purpose of better understanding the relations within the product value chain, and between the value chain and the surrounding technological system.[28] The main characteristics of this approach are the inclusion of the processes to the extent of their expected changes due to a new demand, as well as the application of system expansion for handling the co-products in multi-product systems.[29]

The implemented approach for defining the system boundaries in this work was the consequential LCA perspective along with system boundary expansion and cut-off procedure. Figure 2 presents the basis for consequential LCA and cut-off procedure that were applied in this analysis. To perform the cut-off procedure for eliminating the similar processes from the system boundary, the mill was required to produce the same amount of pulp and final product, before and after biorefinery implementation. If the mill did not implement the biorefinery process and continued to produce the existing product, the environmental impacts would remain the same as before.

Competing products were the competitors of biorefinery products on the existing market. Consequently and based on the calculation methodology, by transferring all the avoided impacts from the competing products and processes, the environmental benefits and negative impacts were allocated and credited to the new biorefinery strategies and bioproduct portfolios.

Subsequently, the system boundary included the HWE-based biorefinery processes and their input material and emissions, also the fossil- or agricultural-based products that could be partially displaced or substituted by the bioproducts. Moreover, minor changes that would be applied on the pulping process while implementing the HWE-based biorefinery were considered in the system boundary. Figure 3 illustrates the system boundary for C5-sugars and acetate salt production; the cut-off parts are shown in brown color.

It should be noted that nearly similar system boundaries were developed for all the defined HWE-based production pathways. The major differences between the alternatives concerned the use of chemicals and other consumables, environmental emissions and most importantly the differences regarding the individual processes and key operating process units.

LCA is often performed using a functional unit that refers to the output or product of a process or system. However, HWE-based biorefinery options under investigation had different production capacities. Therefore, functional unit in this analysis was considered as the portfolio of products that were generated by different biorefinery options and at the same rate of hemicellulose extraction. In other words, life cycle inventory and life cycle impacts were calculated for a reference flow of approximately 310,000 ton per year of dilute hemicellulose stream (5% solid) that was used for different production pathways. Due to cut-off procedure, the existing pulp and paper mill product was not considered in the functional unit. The operation of the mill and HWE-based biorefinery options was 345 days in a year.

4. RESULTS AND DISCUSSIONS

Following implementation of the LCA methodology and developing rigorous mass and energy balances, inventory data including biomass, energy, water and other resource consumptions were calculated. Competing products, which were produced from alternative sources, were identified. The inventory data including the material input and emissions into water, air and soil were employed for the characterization and evaluation of the environmental impacts. In this assessment, four endpoint impact categories were considered.

Concerning the objectives defined for this LCA analysis, calculations were performed in several steps. Table 1 presents the definition of environmental parameters that were evaluated. Consequential LCA results were assessed to show the incremental potential environmental impacts on the implementation of HWE-based biorefinery process. Overall LCA parameters were related to the impacts of biorefinery processes, and to those of the avoided products and processes. Net results were evaluated by summing up the contributions of all inventory compartments within a defined impact category. Thereafter, net results were normalized to analyze the environmental benefits of integrating a HWE-based process into the case study mill. Ultimately, reduction of GHG emissions was calculated for each biorefinery option based on the ratio between the net climate change impacts and the avoided ones.

LCA Results	Interpretation	Definition
Consequential	Incremental impacts of biorefinery implementation, positive contribution to environmental impacts	
Overall	Incorporating the impacts of avoided processes and products, and the biorefinery impacts	
Net	Sum of the positive and negative impacts of all inventory parameters	$\sum_{i=1}^{5} \text{overall impacts}$
Net normalized	Net results relative to the cut-off case	$\text{Ni} = \frac{\text{Net environmental impact, i}}{\text{Environmental imact of existing mill}}$
GHG reduction	Net climate change results relative to the avoided impacts	$\text{GHGi} = \frac{\text{Net climate change impacts, i}}{\text{Displaced climate change impacts, i}}$

Table 1 - Evaluated LCA environmental parameters

4.1 Consequential environmental results

Breakdown of the ‘cradle to gate’ environmental results related to HWE-based production pathways are shown in figure 4.A to figure 4.D. Analysis of the model behind the results reveals that the differences in environmental impacts of defined biorefinery options can be explained by: 1) differences in energy consumption, particularly bark utilization for providing steam, also electricity consumption; 2) differences in types and quantities of chemicals and consumables such as sulfuric acid, enzyme, and lime; 3) differences in production capacity of each biorefinery option that contributes to different bioproduct transportation results.

Following a detailed energy analysis and considering the complete integration of biorefinery to the case study mill (in terms of mass and energy), steam and electricity requirements for the mill and biorefinery processes were evaluated and incremental energy demand due to biorefinery implementation was calculated. Energy Island at the existing mill consisted of two types of boilers for the steam production, which used biomass and oil as fuel sources. In this evaluation, it was assumed that bark boilers would exclusively be responsible to provide the additional required steam for the biorefinery processes. Table 2 presents the bark consumption in order to provide incremental required steam for the defined HWE-based biorefinery options.

	Biogas	Hemicellulose for animal feed and acetate salt	Hemicellulose for C5 sugars and acetate salt	C5 sugars and acetate salt	Furfural and acetate salt
Required bark for biorefinery (BDt/day)	77	116	106	127	151

Table -2 Incremental required bark for biorefinery options

Based on the process design, biogas would partially substitute bark consumption at the existing boilers and resulted in lower steam and bark demand, when compared with other options. On the contrary, total bark consumption for the furfural and acetate salt production process was evaluated to be approximately 151 BDt/day, which was higher than other process alternatives. Following the energy balances, most of the steam consumption for this process was related to stripping columns for the furfural purification. Furthermore, steam demand for the C5-sugars and acetate salt option was relatively high due to energy consumption for the enzyme production to be used in enzymatic hydrolysis. This process was energy intensive and energy was considered in terms of required steam as energy carrier.

Burning barks at the existing bark boilers was nearly a carbon neutral process, i.e. CO_2 that was generated from combustion of barks was considered as biogenic CO_2. Examples of biogenic CO_2

emissions include but are not limited to CO_2 from the combustion of biogas, CO_2 generated from the biological decomposition of waste in landfills and wastewater treatment, CO_2 resulted from combustion of biological material, including all types of wood and wood wastes, forest residues, and agricultural materials.[30] However, the complete life cycle of the bark as the main energy source could not be considered as an entirely carbon-neutral process. While CO_2 emissions from the bark combustion were considered as zero, the whole life cycle of bark has to be included in the environmental analysis. Although the biomass-harvesting step was presumed to perform sustainably, there were still significant emissions resulting from processing and transportation of bark to the mill's site. Consequently, it was proved that barks procurement and transportation was one of the most important process parameter that contributed to major environmental impacts, particularly the resources consumption.

Similarly, incremental electricity demand due to biorefinery integration was evaluated and according to the results, calculated power consumption of all the defined HWE-based biorefineries was relatively the same. Nonetheless, C5-sugars process was the significant power consumer due to the additional electricity demand for the enzyme production. For modelling the electricity consumed by different processes in the life cycle, data from the current average Quebec electricity supply was used.

River water considered to be used as the water source for the biorefinery process options. River flows are resources that are constantly regenerated, however, still there is no consistent and clear metric for this type of resources and clear damage factors have not been calculated for them.[31] Consequently, impacts related to water withdrawal and turbined water was disregarded in this analysis; these impacts were mainly included in the foreground system and characterized by the resource consumption.

Simple transportation model was employed in this analysis, assuming that the distance ranges were between 120 km and 500 km for the transport of biorefinery products to the targeted potential customers. For the barks used in the existing boilers, a transportation distance of 100 km to the mill was considered.

Consequential environmental analysis demonstrated favorable results for the biogas option since biogas would partially substitute bark consumption at the existing boilers. Therefore, no environmental impact resulting from bioproduct transportation was considered for this option. In addition, CO_2 generated from biogas combustion was considered as biogenic one. Conversely, anaerobic processing for the biogas production contributed to a relatively high impact on the climate change results.

Process options related to hemicellulose for animal feed and hemicellulose for C5-sugars had relatively similar production capacities and process conditions. Therefore, the evaluated environmental results of these options were fairly similar. Due to the higher load of effluent streams to the existing-modified wastewater treatment plant, impacts associated with effluent treatment were significant. The main difference between these options corresponded to the additional required steam for the higher concentration (70%) that was required for hemicellulose for animal feed application.

For the C5-sugars and acetate salt and due to the additional steam requirement for the enzymatic hydrolysis, impacts resulted from bark consumption (127 BDt/day) were substantial. Microbial components and electricity consumption for the enzyme production and the consumed chemicals were recognized to be the key contributors in the environmental results attributed to this process option.

Consequential LCA analysis revealed that furfural and acetate salt production contributed to substantial environmental impacts. Following the energy balances, this option required more steam for furfural purification (bark: 151 BDt/day). For this process option, chemicals demand, including sulfuric acid for dilute acid hydrolysis and lime for gypsum removal played a significant role in the evaluated environmental impacts, particularly on the climate change and human health.

4.2 Overall environmental results

Subsequent step in the LCA analysis was to incorporate the environmental impacts associated with displaced processes and competing products. Identification of products that are likely to be substituted or displaced by biorefinery products is a critical step in the life cycle inventory and system boundary definition. In this study, competing products considered as those that were produced from fossil or agricultural resources. In addition, bioproducts entering the market were assumed to displace an equivalent quantity of functionally equivalent products from alternative production routes. Therefore, equivalency ratio was defined to calculate the substitution quantities of displaced products. Table 3 presents the HWE-based biorefinery products resulting from same rate of the extracted hemicellulose stream and the competing products.

Sugar from sugarcane was selected as the competing product for the biorefinery products including hemicellulose for C5-sugars and C5-sugars. Process yield for the production of C5-sugars was taken into account for calculating the amount of substitute products. According to a detailed market survey, the targeted application for these biorefinery products was for xylitol production. Xylitol as a functional sweetener has the same sweetness as regular sugar; however, the absorbed calorie of xylitol is 40% less than that of the sugar, improving its functionality especially for the diabetics and for preventing obesity.[32] For maintaining the same functionality, equivalent sweetness to intake-calorie ratio was considered as the basis for comparison.

Biorefinery product	Production capacity (t/y)	Competing product	Equivalency ratio	Remarks
Biogas	5.2×10^6 (m3/yr)	Bark for Boilers	28 (BDt/day) Dry bark, Same functionality	100% of biogas replaced part of bark at the boilers
Acetate salt	2400 & 14000	Acetate salt from methanol carbonylation	1 Same product	Well-known industrial process, Methanol was produced from natural gas
Hemicellulose for animal feed (70%)	22000	Molasses (72%) from sugar beet	1 Same product	Molasses was a by-product of crystallization process of sugar juice at the sugar refinery
Hemicellulose for C5-sugars (50%)	29000	Sugar from sugar cane	1.6 Same functionality	Sugar displaced by xylitol, with the same sweetness. Considering 40% reduction in absorbed calories
C5-sugars	10000	Sugar from sugar cane	1.6 Same functionality	Sugar displaced by xylitol, with the same sweetness. Considering 40% reduction in absorbed calories
Furfural	5000	Phenol	1.1 Same functionality	Phenol and furfural as usual solvents for extraction of lubricating oil

Table - 3 HWE-based biorefinery products and displaced/competing products

Furfural is a chemical that can be used for several applications including recovery of lubricants from cracked crude, feedstock for the production of furan resins (furfuryl alcohol resins) and flavor compound.[33] Following market analysis, an interesting application for furfural identified to be as a solvent for lubricating oil extraction. In addition, phenol was recognized to be the chemically equivalent product to furfural with the same functionality.[34] For calculating the functionality equivalencies, the raffinate yield and solubility of both solvents were considered.

Breakdown of the overall environmental results and relative contribution of each HWE-based biorefinery option along with displaced process/products to the end-point impact categories are presented in Figures 5.A to 5.D. For the purpose of modelling and calculations, negative values of the inventories were considered for displaced products and processes. Thus, negative bars represent the impacts of these processes while positive bars are related to the consequential impacts of HWE-based biorefineries.

For all the defined biorefinery options, capacity of the existing pulp production line at the mill was maintained constant and hemicellulose pretreatment process was added to the fiber line. Considering the current pulping process at the case study mill, not only no additional woodchips feedstock was required for the mill and the HWE biorefinery process, but also biorefinery implementation resulted in improvements in the pulping yield and savings in incoming wood chips (about 50 BDt/day). Consequently, for all the defined options wood chips savings contributed to overall environmental credits.

Concerning the overall environmental impacts related to climate change and resources use, negative results for the furfural process option were associated with phenol, as the identified product substitute. In this option, phenol considered to be produced from fossil-based resources. Furthermore in biorefinery options related to hemicellulose for C5-sugars and C5-sugars, the displaced impacts of the competing product transportation were significant. Particularly, negative results were due to the avoided impacts relative to the import of sugarcane from Brazil to a sugar refinery in Canada. Moreover, consumption of pesticides and chemicals during the life cycle of sugarcane production contributed to considerable environmental impacts.

Regarding the overall ecosystem quality impacts and in the case of hemicellulose for animal feed and acetate salt biorefinery, displaced impacts relative to molasses production from sugar beet were identified to be positive. It implied that molasses from sugar beet contributes to environmental credits rather than negative results.

4.3 Normalized environmental results

Net environmental results were calculated by adding up the positive and negative overall impacts of all inventory parameters, within a defined impact category. To provide an overview on the environmental performance of different HWE-based biorefinery option, net overall results were normalized. Normalization is an appropriate approach to present the net environmental impacts in a comparable manner by using a reference value.[35] In the present analysis, this value was the environmental impact of the existing mill that was considered as the cut-off part. The objective was to characterize the environmental benefits and improvements in the evaluated impacts, due to implementation of different biorefinery strategies and compared to the paper production. As illustrated in Table 1, normalization was based on calculating the ratio between the net environmental impacts and the impacts related to the paper production. Figure 6 shows the normalized environmental results of the HWE-based biorefinery options.

Positive values represent environmnetal improvements relative to the exising mill's performance and negative values show the negative improvement. Considering the calculated results, hemicellulose for C5-sugars and acetate salt and C5-sugars and acetate salt production processes demonstrated significant performance by having improvements in all the environmental impact categories. Particularly, the human health impacts were decreased by more than 3 times, compared with the existing paper production process.

Furfural and acetate salt process presented relatively favorable results: climate change improvement by 15% and decrease in resources consumption by 43%. As it was expected, due to internal use of biogas at the existing boilers of the mill and its low production volume, this option did not demonstrate considerable environmental improvements. The worst biorefinery option was identified to be the hemicellulose for animal feed and acetate salt production since all the environmental impact categories, particularly ecosystem quality, were increased.

4.4 GHG reduction results

One important parameter for the development of biorefinery processes is an improvement in the environmental performance of bioproducts, compared with products that already exist in the market. In particular, reduction of GHG emissions is often a major driver for the sustainability justification of biorefinery projects, and a key parameter that contributes to the success of these projects. GHG emissions represent the carbon footprint of the processes in terms of CO2 equivalent. For the sustainable strategic biorefineries the reduction of GHG emissions by more than 60% is often sought.

As it was shown in Table 1, the reduction of GHG emissions was evaluated considering the net climate change results and impacts from avoided processes and products. Figure 7 illustrates the GHG reduction results for the HWE-based biorefinery options. Process options related to hemicellulose for C5-sugars and C5-sugars demonstrated favorable environmental results, contributing to 80% and 68% of GHG reduction, respectively. Furfural process option also presented 56% of GHG reduction, relative to the phenol and displaced processes at the mill.

Biogas option resulted in 120% increase in the GHG emissions. As previously explained, biogas would be produced and used at the mill site; therefore, the displaced environmental impacts were limited to the avoided wood chips consumption and displaced processes at the mill. These avoided impacts were not significant compared to other biorefinery options. Consequently, the ratio between the net climate change impacts and the displaced products was evaluated to be higher amongst other biorefinery options.

Concerning the hemicellulose for animal feed and acetate salt option and due to the fact that molasses from sugar beet presented positive environmental impacts, the resulting reduction of

GHG emissions was calculated to be 10%, which is not an acceptable value for the purpose of biorefinery implementation.

4.5 Summary of economic and environmental results

Investing in the transformation of the forest industry into a biorefinery involves several challenges due to issues such as uncertainties at early-stage biorefinery process development, process design and scale-up, and financing.[36] A systematic phased approach that takes into account short- and long-term visions can be used to mitigate the uncertainty-related risks.[37] Identification of the most sustainable strategy plays a significant role in the successful implementation of biorefinery projects. A sustainable biorefinery implementation strategy is the one that provides profitability and long-term competitiveness, mitigates market and techlogy risks in a proper manner and presents remarkable environmental performance.

In the previous study (Gilani B. and Stuart R.P., Unpublished), techno-economic analysis of the HWE-based biorefinery strategy with five defined process options was performed. Technology and market risks associated with the options were identified. Phased implementation scenarios for maintaining profitability over short- and long-term also for mitigating the major risks, were defined. It was shown that using a cost perspective, risks associated with biorefinery implementation could be significantly alleviated with a phased approach. In this section, techno-economic results of the previous analysis and present LCA results evaluated for the defined HWE-based biorefinery options are shown in Table 4.

In general, it is well established that to maintain a minimum risk level, a minimum Internal Rate of Return (IRR) of 20% should be sought. For the purpose of sustaining long-term viability, projects with higher risk such as biorefinery technologies should aim for an IRR of more than 30%. In this analysis, a fixed subsidy of 15 million Canadian dollars, to be obtained from the

Investments in Forest Industry Transformation (IFIT) program of Government of Canada, was considered for the biorefinery process options.

			Biogas	**Hemicellulose for animal feed & A.S.**	**Hemicellulose for C5-sugars & A.S.**	**C5-sugars & A.S.**	**Furfural & A.S.**
Economic parameters	CAPEX (M$)		36.1	25.2	22.4	40.9	35.7
	Annual production cost (M$/y)		-0.5	2.8	2.7	9.2	6.8
	Annual revenue (M$/y)		1.8	5.3	4.6	23.3	14.3
	IRR (%)		3.1	3.9	3.1	25.1	14.4
	IRR (%) (with subsidy)		16.2	44.7	96.4	48	36.6
Environmental parameters	GHG reduction (%)		-126	-10	80	68	56
	Net human health (%)		-1.9	-5.2	389	329	5.8
	Net ecosystem quality (%)		-2.8	-35	31.4	23.8	-8.5
	Net resources (%)		-0.7	0.5	24.9	20.3	42.9
Risk parameters	Technology risk	Main product	Low-Medium	Medium	Low-Medium	Medium	Medium
		By-product		Low-Medium	Low-Medium	Low-Medium	Low-Medium
	Market risk	Main product	Low	Medium	Medium	Medium	Medium
		By-product		Medium-High	Medium-High	Medium-High	Medium-High

Table - 4 Summary of economic, environmental and risk analysis results related to HWE-based biorefinery options

Before the subsidy and except for C5-sugars option with the IRR of 25%, none of the HWE-based process options looked economically promising. Nonetheless, according to a preliminary risk assessment, market and technology risks associated with C5-sugars option were identified to be relatively high. By including subsidy, the economic landscape changed drastically and all the defined biorefinery options, excluding biogas, showed considerable project profitability. It was realized that IRR was particularly sensitive to subsidy, especially for hemicellulose for C5-sugars production as a lower capital cost project; IRR was increased from 3% to 96%.

Net end-point environmental impacts relative to the existing paper production process and reduction of GHG emissions relative to avoided processes and products were calculated as well. As previously stated, GHG reduction is regarded as one of the main parameters for favorable environmental performance of a biorefinery and GHG results below 60% are considered as the "show stopper". Hemicellulose for C5-sugars, furfural and C5-sugar options demonstrated favorable GHG reduction results. Particularly, both C5-options resulted in the reduction of 80% and 68%, respectively. These HWE-based options presented substantial improvements in all the evaluated impact categories as well.

Due to the consistency between the economic, environmental and risk analysis results, identification of the sustainable process option was relatively straight forward: acetate salt and hemicellulose for C5-sugars application and acetate salt and C5-sugar biorefinery options were identified to be the most promising and sustainable options.

The analysis presented in this paper can be used to address the environmental implications of HWE-based biorefinery strategy and for the purpose of early-stage decision-making processes.

5. Conclusion

In this study, through a detailed "cradle-to-gate" analysis, consequential LCA results for five HWE-based biorefinery implementation strategies were evaluated. Bark, chemicals and product transportation identified to be as main sources of impacts. Hemicellulose for C5-sugars and C5-sugars presented GHG reduction of 80% and 68%, respectively. Also, normalized results of these options proved a considerable improvement of more than three times in the human health impact category, relative to the existing processes at the mill. Biogas option resulted in 126% increase in GHG effects. Also, hemicellulose for animal feed and acetate salt showed an increase in all the environmental impact categories.

In the context of early-stage decision-making, the environmental results from this work can be coupled with the economic data to facilitate the evaluation procedure of the defined production pathways and to identify the most sustainable biorefinery option.

6. Acknowledgement

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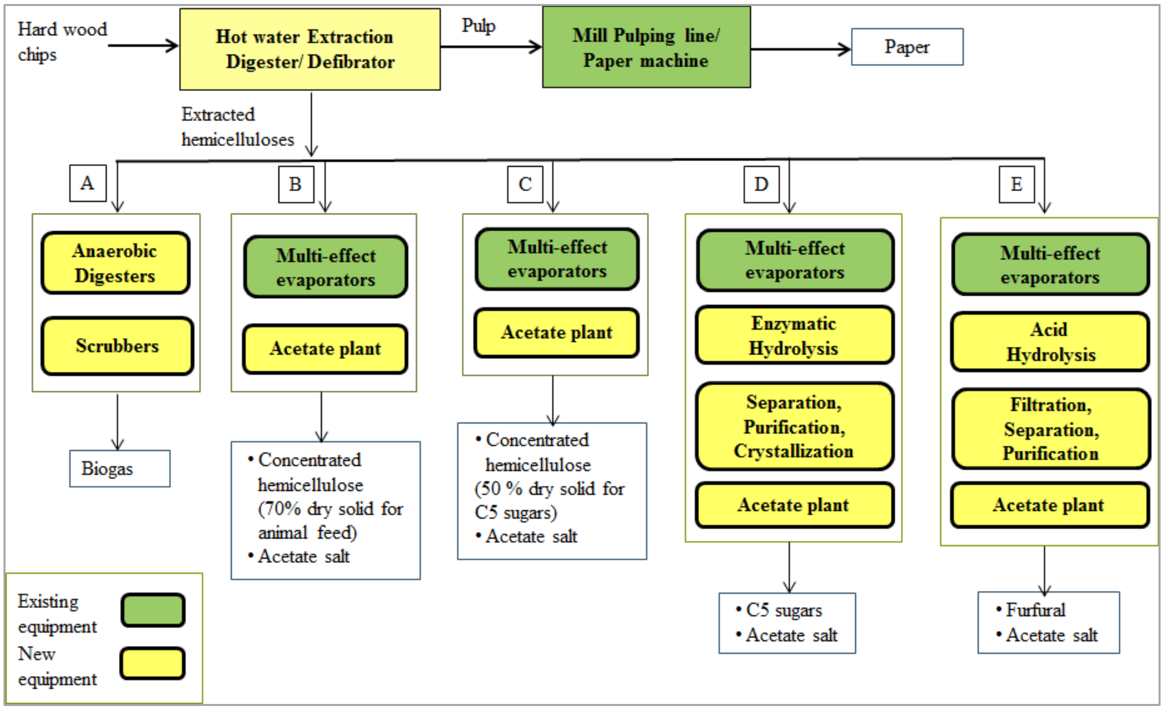


Figure -1 Simplified block flow diagram for HWE-based biorefinery process options

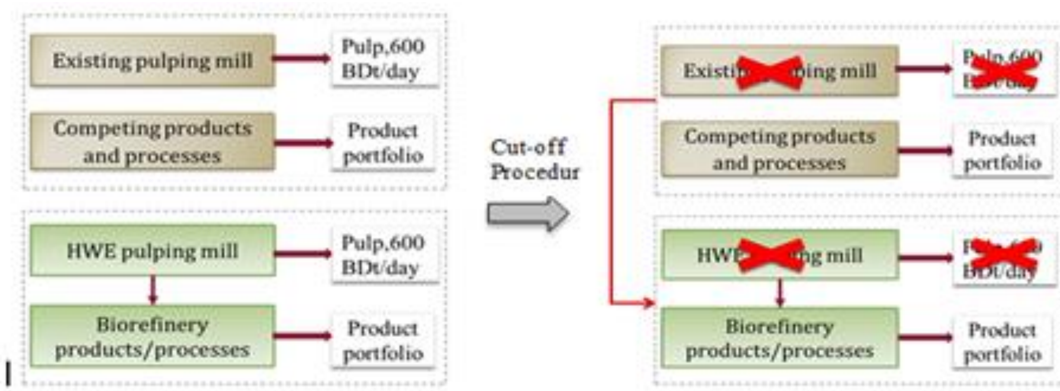


Figure -2 Basis for consequential LCA and cut-off procedure

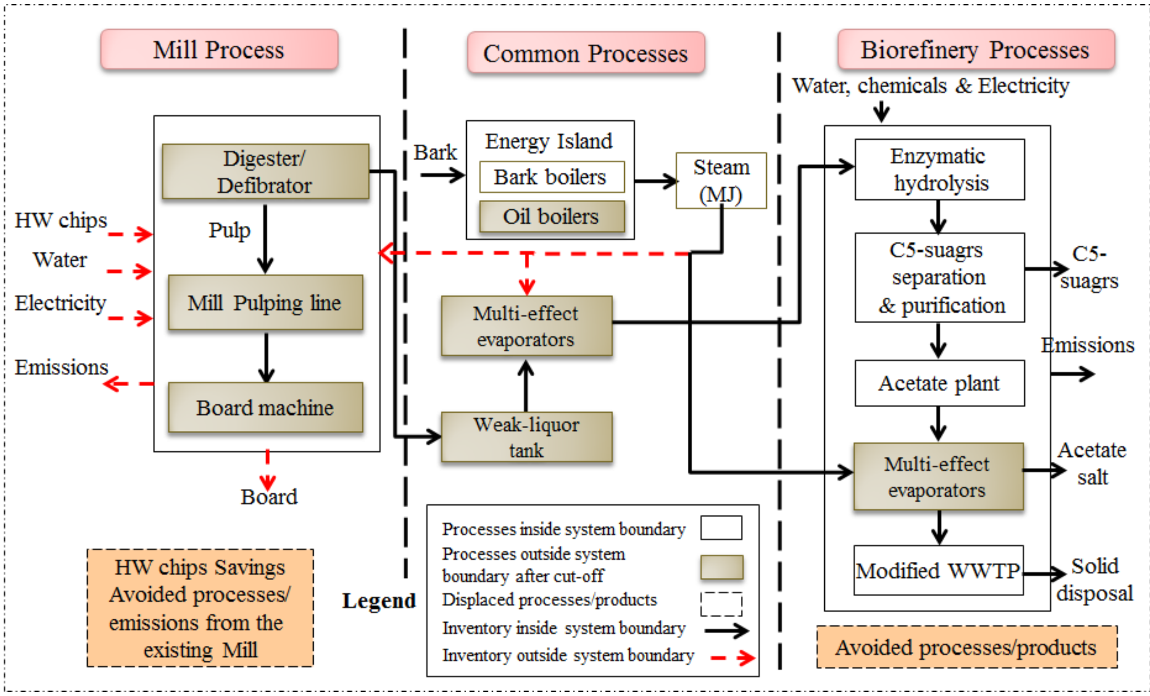
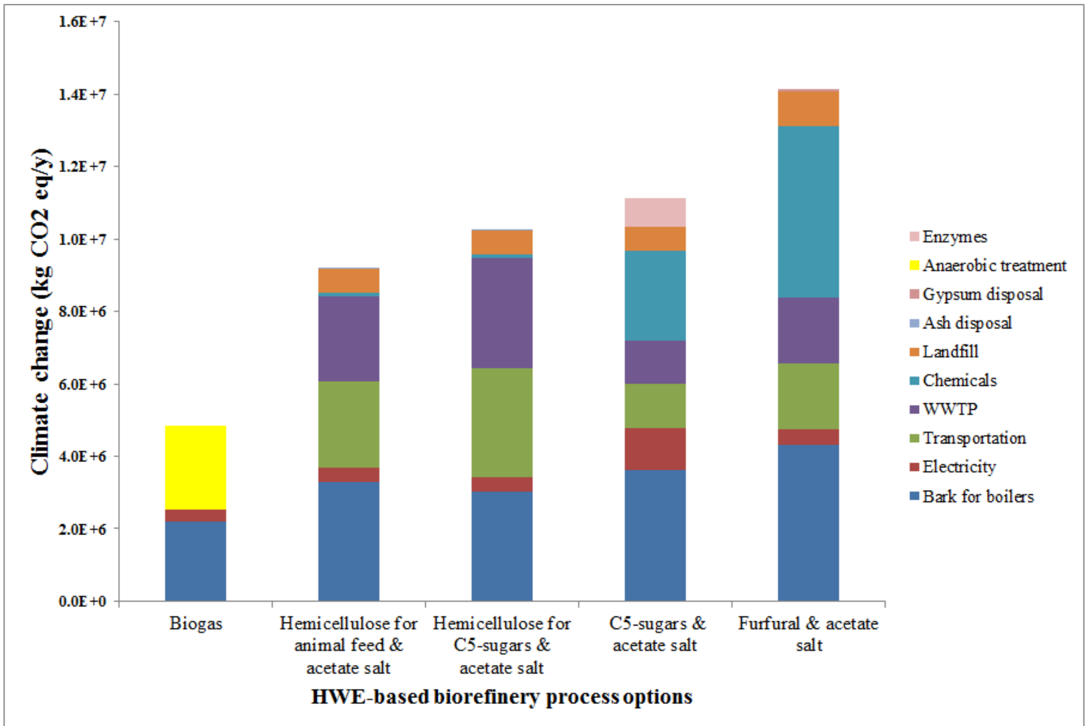
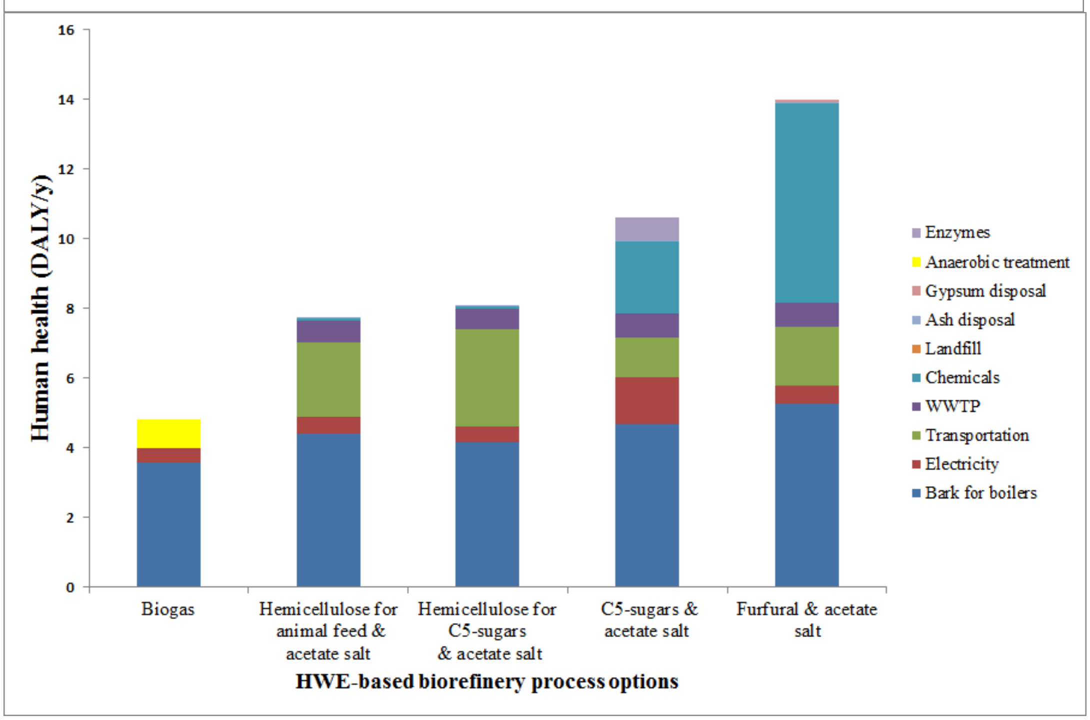


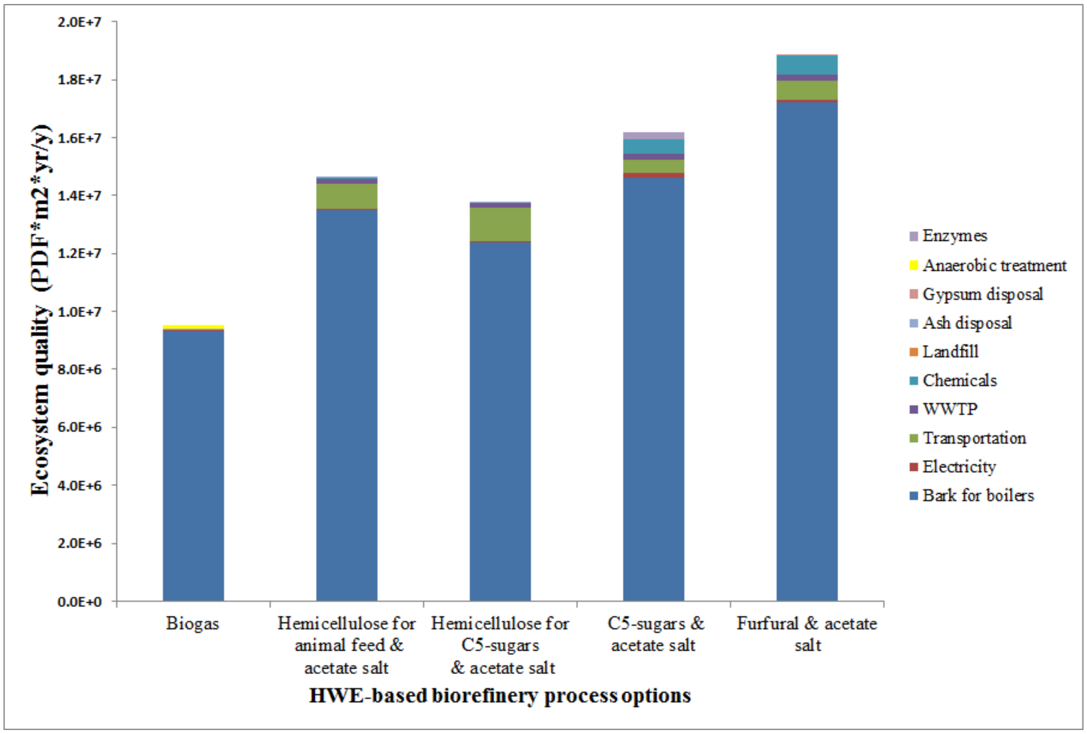
Figure - 3 System boundary for C5-sugars and acetate salt process option


Climate change (kg CO2 eq/y)
1.6E+7
1.4E+7
1.2E+7
1.0E+7
8.0E+6
6.0E+6
4.0E+6
2.0E+6
0.0E+0
Biogas
Hemicellulose for animal feed & acetate salt
Hemicellulose for C5-sugars & acetate salt
C5-sugars & acetate salt
Furfural & acetate salt
HWE-based biorefinery process options
Enzymes
Anaerobic treatment
Gypsum disposal
Ash disposal
Landfill
Chemicals
WWTP
Transportation
Electricity
Bark for boilers

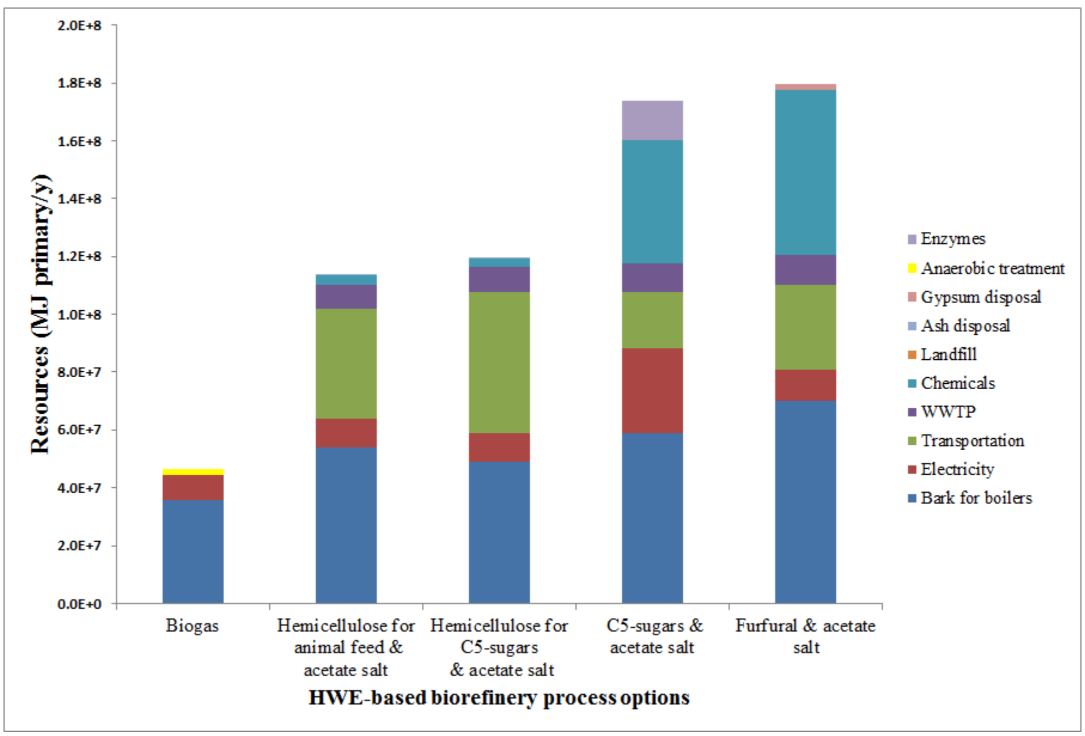
A.


Human health (DALY/y)
16
14
12
10
8
6
4
2
0
Biogas
Hemicellulose for animal feed & acetate salt
Hemicellulose for C5-sugars & acetate salt
C5-sugars & acetate salt
Furfural & acetate salt
HWE-based biorefinery process options
Enzymes
Anaerobic treatment
Gypsum disposal
Ash disposal
Landfill
Chemicals
WWTP
Transportation
Electricity
Bark for boilers

B.

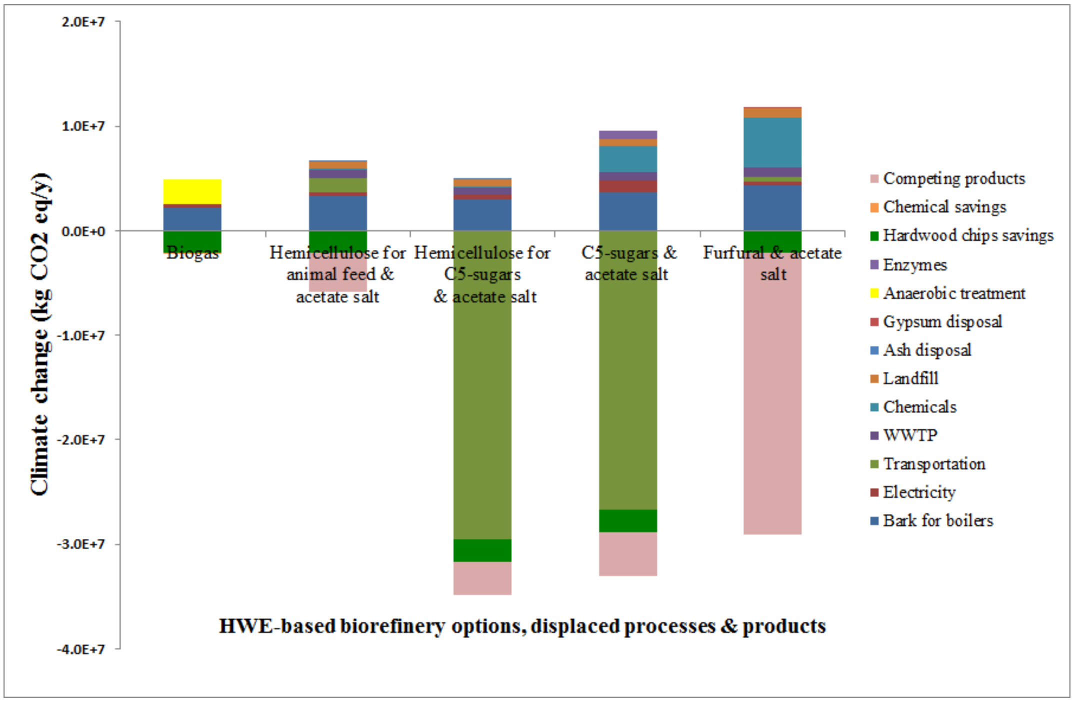


C.

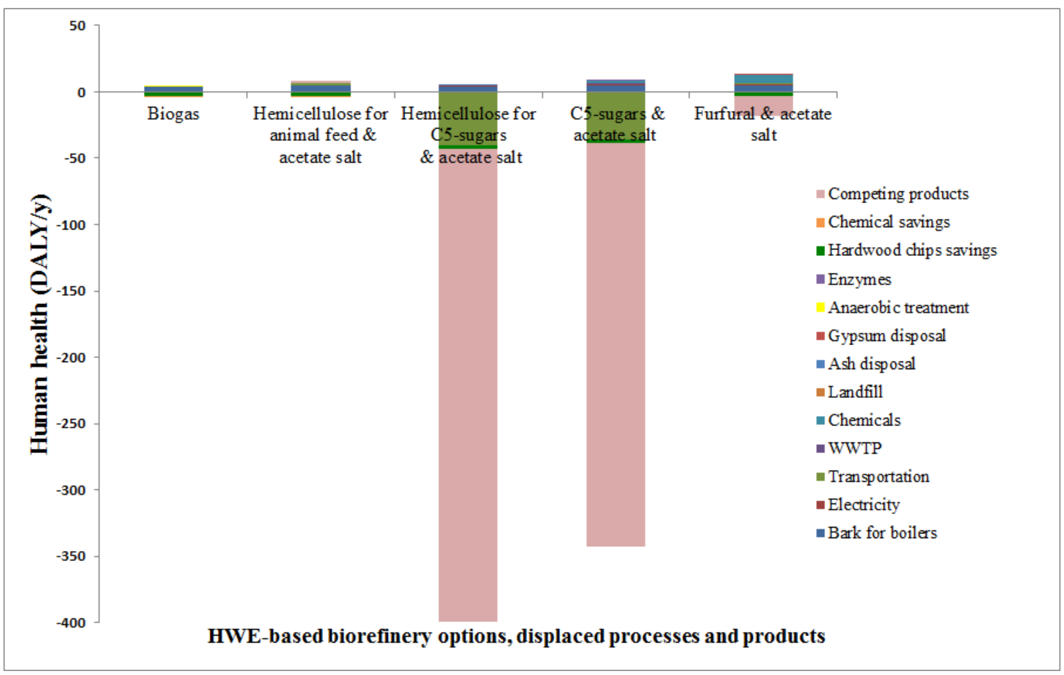


D.

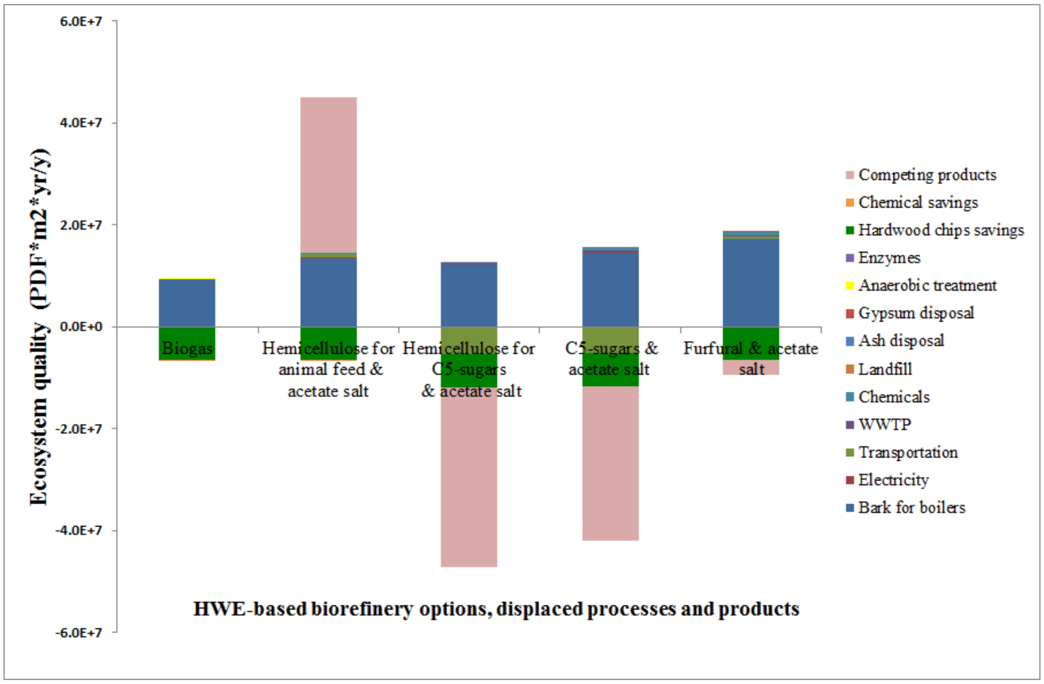
Figure - 4 Consequential environmental results of HWE-based biorefinery options;
A) Climate change B) Human health C) Ecosystem quality D) Resource consumption impacts


2.0E+7
1.0E+7
0.0E+0
-1.0E+7
-2.0E+7
-3.0E+7
-4.0E+7
Climate change (kg CO2 eq/y)
Biogas
Hemicellulose for animal feed & acetate salt
Hemicellulose for C5-sugars & acetate salt
C5-sugars & acetate salt
Furfural & acetate salt
Competing products
Chemical savings
Hardwood chips savings
Enzymes
Anaerobic treatment
Gypsum disposal
Ash disposal
Landfill
Chemicals
WWTP
Transportation
Electricity
Bark for boilers
HWE-based biorefinery options, displaced processes & products

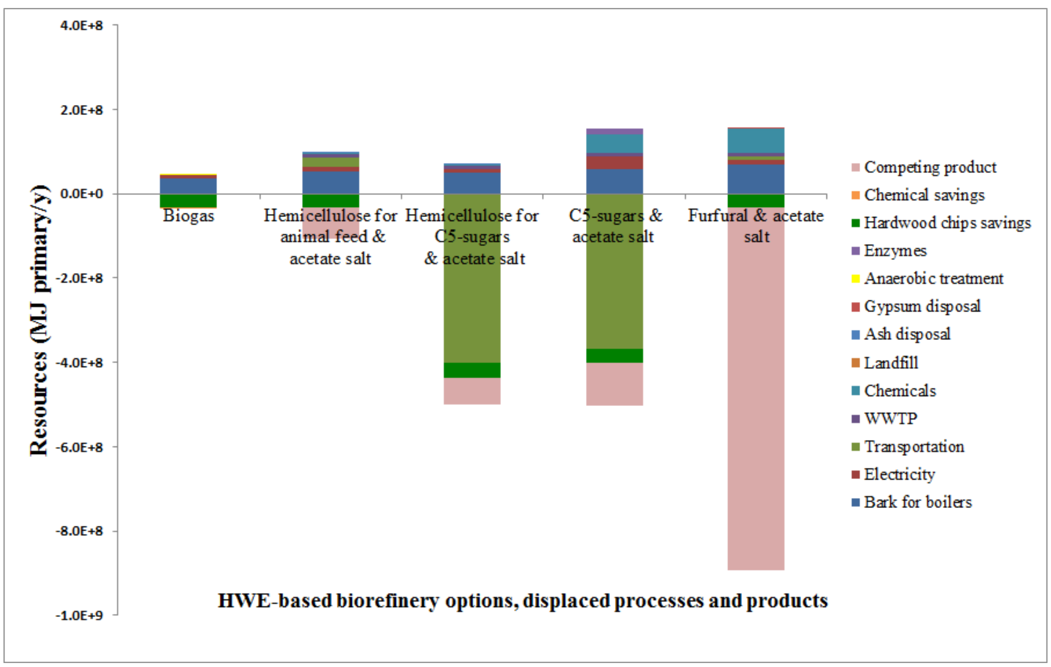
A.


50
0
-50
-100
-150
-200
-250
-300
-350
-400
Human health (DALY/y)
Biogas
Hemicellulose for animal feed & acetate salt
Hemicellulose for C5-sugars & acetate salt
C5-sugars & acetate salt
Furfural & acetate salt
Competing products
Chemical savings
Hardwood chips savings
Enzymes
Anaerobic treatment
Gypsum disposal
Ash disposal
Landfill
Chemicals
WWTP
Transportation
Electricity
Bark for boilers
HWE-based biorefinery options, displaced processes and products

B.



C.



D.

Figure - 5 Overall environmental results related to biorefinery options and displaced products/processes A) Climate change impacts B) Human health C) ecosystem quality D) Resource consumption

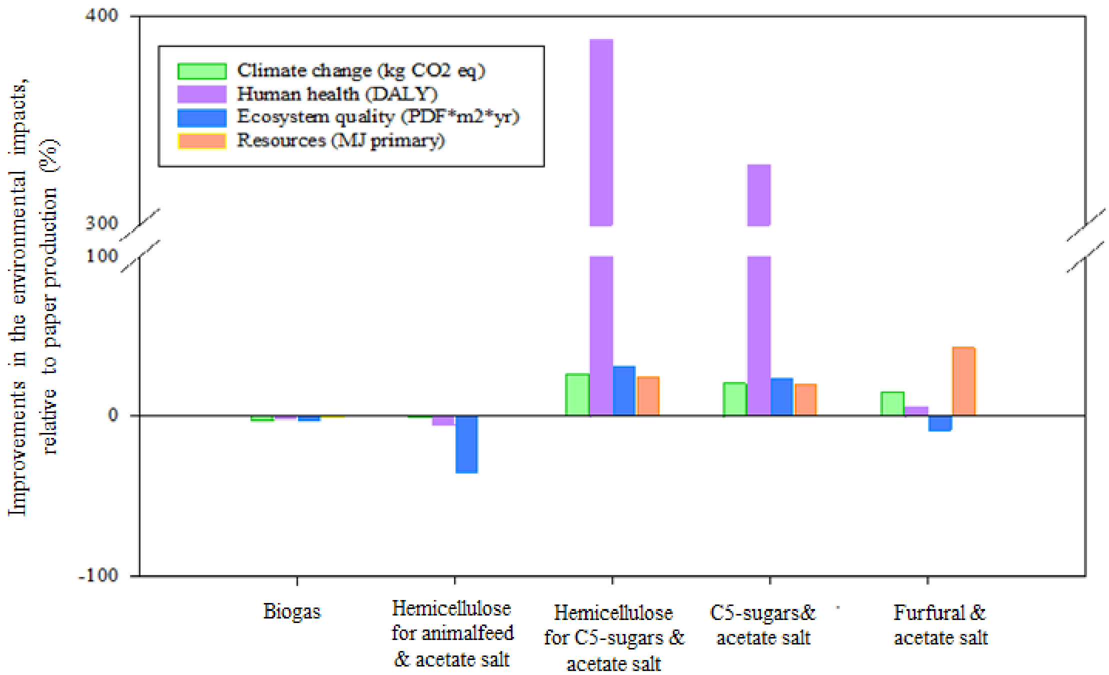


Figure - 6 Environmental improvement results of HWE-based biorefineries elative to paper production

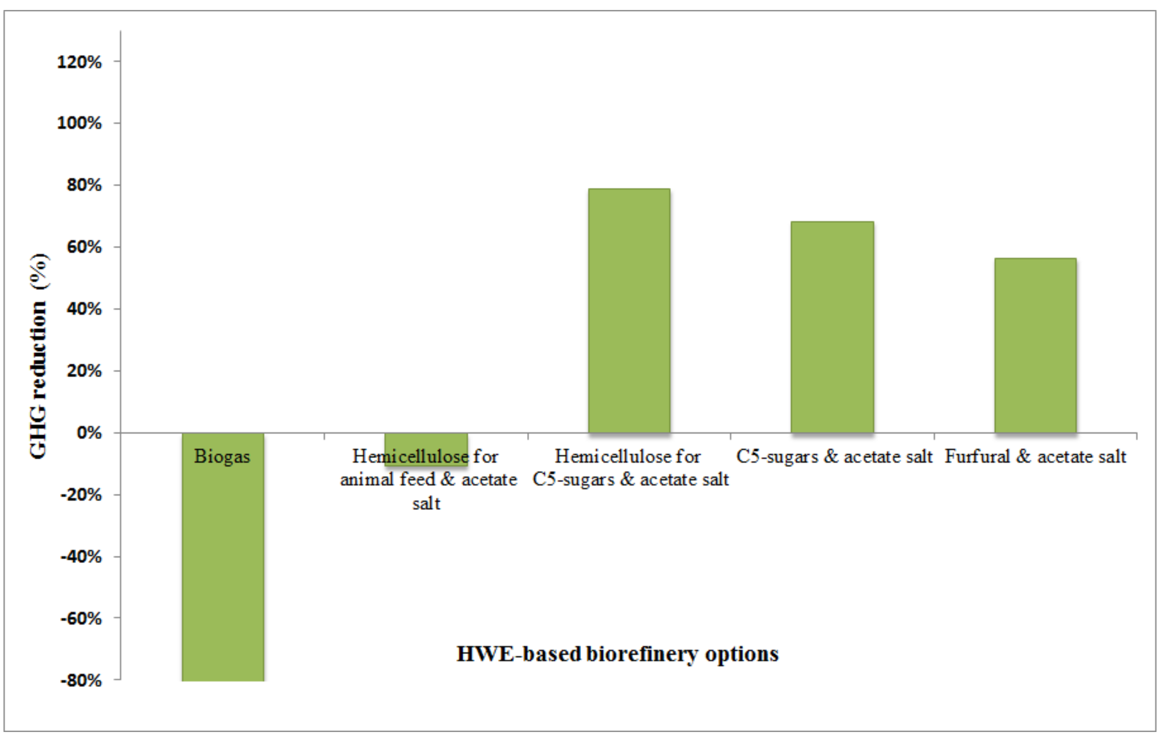


Figure -7 GHG reduction results related to HWE-based biorefinery options